2017

Development of Best Management Practices for Production of Ethiopian Mustard (Brassica Carinata) in South Dakota

Phillip Kenneth Alberti
South Dakota State University

DEVELOPMENT OF BEST MANAGEMNT PRACTICES FOR PRODUCTION OF ETHIOPIAN MUSTARD (*BRASSICA CARINATA)* IN SOUTH DAKOTA

BY

PHILLIP KENNETH ALBERTI

A thesis submitted in partial fulfillment of the requirements for the

Master of Science

Major in Plant Science

South Dakota State University

2017

2017

DEVELOPMENT OF BEST MANAGEMNT PRACTICES FOR PRODUCTION OF ETHIOPIAN MUSTARD (*BRASSICA CARINATA*) IN SOUTH DAKOTA

PHILLIP KENNETH ALBERTI

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science degree in Plant Science and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thandiwe Nleya, Ph.D.
Research Advisor — Date

Febina Mathew, Ph.D.
Academic Advisor — Date

David Wright, Ph.D.
Head, Department of Agronomy, Horticulture and Plant Science — Date

Dean, Graduate School — Date

There are many people I would like to dedicate this research to. To my mother, Lisa, for being the most self-less and loving person on this planet; you have dedicated your entire life to your family and I can only hope I do the same for my own. To my father, Daryl, for teaching me to live my life my way and never stop pursuing what I want; you taught me not only to strive to meet my goals, but to be a good man achieving them. To my brother-hero Brandon, you have been and will always be my mentor and best friend; I would not be here today if you had not been there to guide me every single step of the way. To my sister Lindsay, for the countless times we have had conversations without speaking; you have been a true blessing in my life, thank you for letting me out of the "Cage." To my sister, Andrea, for always being my partner-in-crime; you and I moving away from home brought us closer together and no one will ever know me like you do. To my (twin) sister Jandelle, you have always put the needs of our family above your own; you are my angel (you get that from mom) and are by far the best of us. To my sister Jenna, whose joie de vivre is infectious; you are so incredibly talented and are going to do great things, my dear. To Erin, you really are my everything; I can't imagine my life without you, nor would I want to. To Alyssa, for being the strongest woman I know and being there for ALL of it; through the good and bad, our lives are intertwined. To Cristian and Parker, for always being there and for keeping the group chat alive since I left; you two kept me sane on this journey and are the best, men. To Chris and Patrick, thank you for your never-ending support and guidance; you both have become brothers to me. I love you all. To the countless others who have helped me along the way, your support means everything.

ACKNOWLEDGEMENTS

Foremost, I would like to profess my sincere gratitude towards my advisors (Dr. Thandiwe Nleya and Dr. Febina Mathew) and graduate committee (Dr. Shaukat Ali, Dr. Leda Cempellin, and Dr. Shannon Osborne) for their unyielding support and guidance which they have provided me over the duration of my research. Dr. Nleya, thank you so much for constantly keeping me on track and pushing me to do better; you are a wonderful advisor, trusted friend, and I am truly lucky to have had you as my advisor. Dr. Mathew, thank you for encouraging me, always, because you knew that I could do it. Dr. Shaukat Ali; thank you continually guiding me, and consistently making me laugh; you have become more than an advisor to me and are a true example of the impact one teacher can have on a student. I would also like to sincerely thank Christopher Owusu for spending hundreds of hours doing tasks that would make most undergraduates cut and run; I do not know if you will ever truly know how much you helped me. To my technicians Lee Gilbertson and Nathan Braun who made it possible for me to finish this research; special thanks to Lee Gilbertson for coming out of retirement (several times) in order to help me finish my work, I will never forget this. Lastly, thank you to John Posch, Deepak Joshi, and Dr. Dalitso Yabwalo, who were always there for me. John, you have become a trusted advisor, confidant, and friend; the times we had over the last few years are a huge reason I made it out of graduate school alive (mostly) and I will surely not forget them. Thank you all.

This research was supported by funding from the South Dakota Oilseed Initiative as well as the North Central Regional Sun Grant Center at South Dakota State University though a grant provided by the U.S. Department of Agriculture under award number 2014-38502-22598. Thank you to Agrisoma, for providing the materials to make this research possible. Thank you to Dakota Lakes Research Farm, Jorgensen Land & Cattle, and the South Dakota Agricultural Experimental Station for providing the land to pursue this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

ABSTRACT

DEVELOPMENT OF BEST MANAGEMNT PRACTICES FOR PRODUCTION OF *BRASSICA CARINATA* (ETHIOPIAN MUSTARD) IN SOUTH DAKOTA

PHILLIP KENNETH ALBERTI

2017

Ethiopian mustard (*Brassica carinata*) is an alternative non-food oilseed crop which has received interest for its potential as a low-input option for production in the Northern Great Plains (NGP). As *B. carinata* is a new crop to the NGP, the best management practices have yet to be developed. The overall goal of this project was to develop best management practices for *B. carinata* production in two diverse agro-environments in South Dakota. Two field experiments were conducted to assess the response of two *B. carinata* varieties to i) four seeding rates (4.5, 9, 13.5, and 18 kg ha^{-1}) and ii) five N rates (0, 28, 56, 84, and 140 kg ha^{-1}) under opposing agro-environments in South Dakota: Eastern (humid-temperate, conventional tillage) and Central and Western (semi-arid, no-till). Data on plant stand establishment, phenology, agronomic traits, seed yield and seed quality were collected. The results from the seeding rate study showed better stand establishment and yield under conventional till than under no-till. Optimal seeding rates for Eastern (humid temperate, conventional tillage) and Central and Western (semi-arid, no-till) were ~10 and ~13 kg ha^{-1}, respectively. This suggests that higher seeding rates may be necessary to help compensate for reduced stand establishment in drier environments under no-till. The optimal N rate for *B. carinata* production in South Dakota was ~79 kg ha^{-1} N across environments. In conclusion, these results show that N requirement for *B. carinata* is lower than for man crops including

corn and small grains. These findings confirm that *B. carinata* is a low-input crop with a potential for incorporation into cropping systems in the semi-arid regions of the NGP.

DEVELOPMENT OF BEST MANAGEMNT PRACTICES FOR PRODUCTION OF ETHIOPIAN MUSTARD (*BRASSICA CARINATA)* IN SOUTH DAKOTA

INTRODUCTION

Over the last 40 years, production of *Brassica* oilseed species, primarily *B. rapa*, *B.napus, and B. juncea*, have increased steadily on the way to becoming one of the most important sources of biofuel in the world (Rakow et al. 2004). Canada is one of the global leaders in canola grade oil production and is responsible for 20% of the world's supply and 74% of export trade; canola grade oil production from *Brassica* spp. results in $11 billion in economic value. As a result of this large-scale production, the U.S. has become the largest buyer of canola from Canada (McKenzie 2011). Steady increases in production and revenue of canola in the humid-temperate climate of Canada has led to increased interest in canola production in US region of the Northern Great Plains (NGP) with the similar climatic conditions. In the U.S., 90% of canola production is in North Dakota with the remaining production occurring in South Dakota, Montana, and Minnesota (Hanson et al., 2008). While the number of acres planted to canola is small, production is rising every year with the potential to expand greatly across the NGP. This rise in production is due to the desire to diversify cropping systems as well as the ongoing difficulties resulting from widespread Fusarium head blight in cereal crops such as wheat (Pan et al. 2012).

Due to the presence of both humid temperate and semi-arid climates in the NGP, farmers and researchers are actively searching for a more resilient *Brassica* species which can withstand the highly variable environmental conditions as well as the different cropping systems across the region. *Brassica* species currently being used for oil production are sensitive to heat and drought during flowering and seed-filling stages, which can severely limit oil content and yield (Chen et al. 2005). Because of this, research on *B. carinata* production in the semi-arid environments of central and western South Dakota has increased due to its qualities as a drought and heat tolerant oilseed.

B. carinata originated in Ethiopia where it is believed to have been cultivated since 4000 BC for use primarily as a cooked leafy vegetable (Mekonnen et al., 2014). The oil from *B. carinata* seeds contains elevated levels of glucosinolates and erucic acid making the crop not suited for human food or livestock feed. As the demand for oilseed crops for biofuel continues to grow, it is becoming more important to explore non-food oilseed crops such as *B. carinata* to meet this demand. In this light, interest has grown regarding the use of *B. carinata* as a broadleaf crop to diversify and extend crop rotations in wheat (*Triticum aestivum*) or pulse production systems (Agriculture Victoria, 2012). Because *B. carinata* is a new crop in the NGP, there is a lack of information regarding optimal management practices. Thus, there is a need to identify the optimal management practices for *B. carinata* including seeding rate, and nitrogen (N) fertilization for achieving yield and seed quality goals in both humid temperate and semi-arid production zones in South Dakota.

CHAPTER 1

ETHIOPIAN MUSTARD (*BRASSICA CARINATA*) RESPONSE TO SEEDING RATES AT FIVE ENVIRONMENTS IN SOUTH DAKOTA

LITERATURE REVIEW

Brassica carinata, like all *Brassica* species, is a small-seeded crop with lower germination rates and higher seedling mortality than cereal grains. On average only 40-60% of planted canola seeds produce viable plants, with variation occurring due to environmental conditions, farming practices, and variety selection (Canola Council of Canada, 2016). As with most agronomic crops, uniform crop emergence and plant development are crucial to achieving high yields and using the appropriate seeding rate is very important to achieve this goal. Seeding rate is believed to influence many factors of mustard production including: stand establishment, flowering, lodging, disease, seed weight, oil content, and yield. Studies have shown that seeding rate and plant establishment exhibit a positive linear correlation in *B. carinata* (Pan et al., 2012). In general, due to the high variability in stand establishment, the goal for mustard species is to plant in a range that optimizes yield potential while minimizing risk (McKenzie, 2011). Recommended plant populations for *B. carinata* production in the NGP are in the range 86 to 183 plants m^{-2} (Agrisoma 2015). When fields experience poor emergence, weed competition, or damage from frost, hail, and insects re-seeding is often an option. However, mustards are very plastic and can overcome severe stand reduction via branching. Thus, it is generally recommended that the threshold for re-seeding canola-grade *Brassica* species is ~40 plants m^{-2}; this threshold is considered the point at which canola can recover from severe damage without losing significant yield (CCC, 2016). In

B. napus, increased seeding rates can result in higher plant populations, increased above ground biomass, and increased stubble; the same study suggests that increased plant populations can also reduce the proportion of seeds that produce viable plants, (McKenzie, 2011). Increased above ground biomass is an important means to improve plant competition and reduce weed incidence; thus, higher seeding rates may be a desirable option in fields with severe weed pressure (Harker et al., 2012). This is particularly important as mustards compete poorly with weeds at early growth stages but can outcompete most weeds once the crop has established (Grady, 2002). Given these considerations, it is apparent that determining optimal seeding rates is so critical.

When *B. napus* is planted at low seeding rates (~4 kg ha^{-1}), there is less intraspecific competition resulting in plants with stronger stems, increased branching, longer flowering periods, and more siliques (pods) (Angadi et al., 2003). When plant stands are low, *B. napus* has been shown to regulate vegetative propagation by increasing lateral branching as a compensatory mechanism (Angadi et al., 2003; Leach et al., 1999). Additionally, at lower seeding rates siliques form more evenly throughout the plant, particularly on the lower branches which helps reduce lodging severity in adverse conditions (Sarkees, 2013). On the contrary, as seeding rates increase intraspecific competition is increased resulting in smaller plants with thin stems, fewer branches and less siliques. Increased competition between plants increases potential for water and nutrient stress which can inhibit growth and development (Ma et al., 2016). At higher plant densities, *Brassica* species exhibit a greater concentration of siliques on the upper portion of the plant. The increased concentration of siliques in the upper part of the plant coupled with weaker stems can result in severe lodging. Increased lodging in higher plant populations of *B. napus* traps moisture and provides a suitable microclimate for white mold (*Sclerotinia sclerotiorum*) infections to develop, potentially devastating yields (Hanson, 2008). This is particularly important due to the fact that all currently grown *Brassica* species are susceptible to sclerotinia stem rot (Hanson, 2008). Additionally, severe lodging can make harvesting difficult as it reduces uniformity in plant height and maturity (McKenzie, 2011).

In canola (*B. napus* and *B. juncea*), increasing seeding rate has been shown to increase days to maturity, depending on environmental conditions; days to flowering and maturity are increased when the reproductive phase occurs during cool, wet conditions (CCC, 2016). Increasing seeding rates beyond ~100 plants m^{-2} has resulted in reduced flowering duration and increased days to maturity (Inamullah et al., 2013) This is believed to be due to the increase in competition among *Brassica* plants for water, light, and nutrients which can result in delayed and uneven maturity (Gan, 2015). Lengthened maturity periods, which can result in increased yields, increases risk of frost damage and green seed (Hanson et al., 2008; Holzapfel and May, 2015). Green seeds are immature seeds with high levels of chlorophyll which make processing more difficult, and often results in a decrease in profitability for the producers. Conversely, decreasing seeding rates of canola below minimal threshold levels (≤4.5 kg/ha) can reduce days to flower, duration of flowering, and days to maturity by several days (Inamullah et al., 2013). Reduction in the number of days to flowering and maturity may be beneficial to avoid the high temperatures common during flowering and seed filling in the NGP which can decrease yields; similarly, shortened period to flowering and maturity can help reduce risk of frost damage in cooler climates or for late-maturing canola varieties (Kutcher et al. 2010).

The influence of seeding rate on seed quality traits including oil content and seed weight is in dispute. Higher seeding rates have been shown to decrease, increase, and have no effect on oil concentration in canola or rapeseed (Gan et al. 2015; Ma et al., 2016). Reports from Leach et al. (1999) and Morrison et al. (1990) showed that increasing seeding rates increases oil concentration; meanwhile, studies from Van Deynze et al. (1992) and Sharkees (2013) showed that increasing seeding rate decreased oil concentration in rapeseed. Variability among these studies is believed to be due to variation in environmental conditions such as temperature, rainfall, and soil physical and chemical characteristics. Seeding rate has been shown to have no influence on seed test weight, suggesting that increases in yield are attributed to other factors such as the number of pods plant^{-1} and seeds pod^{-1} (Ma et al., 2016). Oil content is often one of the more important factors in *Brassica* species production, with higher oil content of seeds resulting in higher seed quality and increasing profitability for the producers. In addition, results regarding the effect of seeding rate on seed weight has been varied; higher seeding rates have been shown to decrease, increase, and have no effect on seed weight in rapeseed (Sarkees, 2013; Harker et al., 2012). Seed weight is another important aspect of seed quality; with yields generally increasing as seed weight increases due to the increase in protein content (Pan et al., 2012).

Seed yield is a function of the effects and interactions of many genetic and environmental factors including: temperature, moisture, tillage practices, population density, number of pods plant^{-1}, number of seeds per pod, and seed weight. Data regarding the influence of seeding rate on yield in mustards has been quite inconsistent. In a survey of 65 site-years of seeding rate studies of *B. napus*, the results have not been agreeable; 23 suggested that seeding rate had no effect on yield, 11 showed that a seeding rate of less than 6.7 kg ha^{-1} produced greatest yields, 17 showed that rates between 6.7 and 9 kg ha^{-1} produced greatest yields, and 14 showed that a seeding rate of greater than 9 kg ha^{-1} produced the greatest seed yields (McKenzie, 2011). This research, along with a study done by Ma et al., (2016) suggests that as seeding rates increase the number of siliques and seeds pod^{-1} decrease, resulting in similar yields to lower seeding rates. Another study, featuring a hybrid canola cultivar conducted by the Agriculture Canada in Alberta, showed that lowest yields were found at the lowest seeding rate, 75 seeds m^{-2} (~5.6 kg ha^{-1}), but there was no significant difference in yields when seeding rates were increased up to 275 seeds m^{-2} (~17 kg/ha) (McKenzie 2011); this suggests while yields are relatively insensitive to seeding rate, there is a seeding rate threshold that must be exceeded to optimize yields (Potter 1998). Despite the contradicting results, it is still well observed that mustard species have great yield plasticity. The yield plasticity is due to the compensatory branching ability of *Brassica* species in response to environmental conditions such as water, light, and nutrient availability (Chen et al. 2005; Pan et al., 2012). Conversely, extremely low plant densities are not able to compete with weeds or utilize light, moisture, and nutrients fully which can result in a yield penalty. The ability of canola to “self-thin” and reduce plant populations when competition is too high among plants is well documented; this compensatory mechanism has been known to mitigate yield losses (CCC, 2016). In short, research shows that *Brassica* spp. have an ability to compensate for high and low seeding rates and plant populations with negligible effect on yield.

In South Dakota the agro-ecological systems shift from eastern humid-temperate to semi-arid western prairies; the change from humid to semi-arid climates approximately follows the Missouri River. These diverse climates and subsequent variation in farming practices have large implications for crop production practices and yield potential, with seeding rate being a crucial factor. For this reason, seeding rate requirements in South Dakota are variable according to several environmental factors: climate (humid vs. semi-arid), farming practices (conventional tillage vs no-till), and variety selection. Failure to use appropriate seeding rates can have severe impacts on weed suppression, yield (seed and oil) and quality. Because *B. carinata* is a new crop to the NGP, there is no information about the optimum seeding rates for production in the diverse agro-environments in South Dakota. he objective of this research was to i) evaluate the response, in seed yield and other agronomic traits, of two *B. carinata* varieties to four different seeding rates, ii) determine if variety x seeding rate interactions occurred, and iii) determine the seeding rate for economic optimum yield at two agro-environments in South Dakota.

MATERIALS AND METHODS

The study was conducted at three locations, Brookings (44.368765ºN, -96.788531ºW), Ideal (43.558586 ºN, -99.911416ºW), and Pierre (44.292860ºN, -100.006049ºW) in South Dakota in 2016 and 2017. Soil chemical and physical characteristics can be found below in Table 1.1. In 2016, the Brookings study was located within Felt Family Farm, approximately 6 miles north of Brookings; in 2017, the Brookings study was located at Aurora Agricultural Experimental Station, approximately 8 miles east of Brookings. In 2016 and 2017 at Pierre, the experiment was conducted at Dakota Lakes Research Farm. At the Ideal location, the experiment was conducted at Jorgensen Land & Cattle in 2016 and 2017; however, in 2016, the experiment was lost due to Starane® Flex (Florasulam, Dow AgroSciences, Indianapolis, IN) drift from an adjacent oat field. While most soil characteristics were similar across years at each location, in 2017 the Ideal location had significantly greater residual soil N prior to planting than the other locations. Slightly basic soil conditions in Pierre and Ideal in 2017 differ from the slightly acidic soil conditions seen in Pierre (2016) and Brookings.

The experimental design was a randomized complete block (RCBD) design with treatments replicated four times. Treatments included four different seeding rates (4.5, 9, 13.5, and 18 kg ha^{-1}) and two *B. carinata* cv. (‘A110’, ‘A120’in 2016 and A120, and ‘M01’ in 2017) were arranged in a factorial design to give a total of eight treatments within each replication, for a total of 32 plots per location per year. In 2016, the planting dates were April 26 at Brookings and April 15 at both the Ideal and Pierre locations. In 2017, the planting dates were April 24 at Brookings and April 22 at both the Ideal and Pierre locations. Planting was accomplished using a seven-row Hege 500® (Wintersteiger- Austria) at Brookings; seeding at Pierre and Ideal was done using a Light Duty Grain Drill® (Almaco- Iowa). For the Brookings location, individual plot size was 1.62 x 9.14 meters (14.86 m^2) and 1.62 x 8.23 meters (13.37 m^2) at Pierre. Each plot had seven rows, 22 cm apart and the seed was placed at a recommended depth of 1.27-2.54 cm (Seepaul et al., 2015).

In 2016, 56 kg ha^{-1} N fertilizer in the form of urea (46% N) was broadcast manually using an automatic hand-held spreader to ensure even application ~4 weeks after planting. In 2017, 112 kg ha^{-1} N and 22 kg ha^{-1} S in the form of urea (46% N) and ammonium sulfate (21% N and 24% S) mixture was applied in a split application as recommended to ensure continuous supply of N (Seepaul et al., 2015). The first application occurred at planting and the second application occurred around the bolting stage. The fertilizer was broadcast manually using an automatic hand-held spreader to ensure even application.

Weeds were managed with pre-plant application at all locations of Prowl H_20 (Pendimethalin, BASF, Research Triangle, NC) herbicide. The herbicide was applied at a rate of 2.8 L ha^{-1} and incorporated 5 cm deep via two-pass incorporation. Additional herbicide application at Ideal in 2017 included 30% PowerMax (Glyphosate, Monsanto, Saint Louis, MO) applied at a rate of 1.2 L ha^{-1}. Herbicide application was at approximately two weeks before planting for all locations and years. Once the crop had emerged, weeds were managed by manually removing weeds from within each plot as necessary.

Four weeks after seeding, plant stands were assessed by counting the number of plants in a 4 ft^2 square; estimates of plants m^{-2} were then calculated. Days to flowering (50% of flowers open within each plot) and days to maturity (50% of plant with pods turned yellow within each plot) were also determined for each plot. At physiological maturity, average plant height was determined by measuring height of five random plants within each plot from soil line to the top of the plant. Lodging notes were taken and rated on a scale from 1 to 9 (1= no lodging, 9= completely lodged). Shattering notes were taken based on percent of pods shattered at the time of harvest within each plot. Whole plant samples were obtained from all plots and both locations, and the number of seeds per 15 pods and number of pods per 10 plants were determined. From these values, the average number of seeds pod^{-1} and pods plant^{-1} were determined.

Once *B. carinata* had appropriately dried down, it was harvested using a Kincaid 8XP® crop research combine (Kincaid Equipment and Manufacturing- Haven, KS) with the assistance of the H2 High Capacity GrainGage® (Juniper Systems Inc.- Logan, UT). In 2016, the *B. carinata* was harvested on August 9 at Brookings and August 5 at Pierre. In 2017, the *B. carinata* was harvested on August 21 at Brookings and August 11 at Ideal and Pierre. Once the plots were harvested the seed was cleaned using a sieve and a blower to remove unwanted plant material; cleaned seed was collected and total seed yield (kg) was determined. Sub-samples of the harvested seed were collected and placed into individual manila envelopes and stored in a cold room (~10º C) for oil content determination. Two replications for all seeding rate treatments were sent to SGS Mid-West Seed Services, Inc. (Brookings, SD, USA) for oil content analysis using a hexane solvent extraction. The results of this analysis were used to calibrate the “minispec mq” (Bruker- Billerica, Massachusetts) NMR instrument for further *B. carinata* oil analysis. The remainder of the samples from both years and locations were then analyzed using the “minispec mq.”

A combined analysis included all data collected from three locations (Brookings, Pierre, and Ideal) over 4 seeding rates (4.5, 9, 13.5, and 18 kg ha^{-1}), and three varieties (‘A110,’ ‘A120,’ and ‘M-01’). Data was analyzed using Rstudio (The R foundation, Vienna, Austria- 2016) to determine whether the interactions between seeding rate, variety, and location influenced the agronomic traits evaluated. Fixed effects in the models were “seeding rate,” “location,” and “variety.” The random effects in the model were “year” and “replication,” which acted as a block. Lodging severity scores were not transformed and were analyzed parametrically; this is because normality of model residuals was confirmed using Q-Q and residual versus fitted diagnostic plots (Figure A.1. and A.2.). The agronomic traits were analyzed using analysis of variance (ANOVA) for a RCBD in RStudio (v0.99.903; https://www.rstudio.com/) using the package “agricolae” (deMediburu, 2017). Fisher’s Least Significant Difference (LSD) was used to compare the differences among treatments at the 95% confidence level. This analysis showed significant location x seeding rate interactions for most agronomic traits, suggesting each location should be analyzed separately (Table A.1). Next, for each location in each year, data was then analyzed separately to better understand differences due to variation in tillage practices, variety selection, and climate.

Individual analysis included data collected from four seeding rates, and two varieties to determine whether the interactions between seeding rate and variety influenced the agronomic traits evaluated at each location; variety selection varied from year and location. Fixed effects in the models were “seeding rate” and “variety.” The random effect in the model was “replication,” which acted as a block. The agronomic traits were analyzed using analysis of variance (ANOVA) for a RCBD in RStudio (v0.99.903; https://www.rstudio.com/) using the package “agricolae” (deMediburu, 2017). Fisher’s Least Significant Difference (LSD) was used to compare the differences among treatments at the 95% confidence level.

Yield data was used to perform an Economic Optimum Seeding Rate (EOSR) analysis according to environmental conditions (tillage practices and climatic conditions) in South Dakota. Separate EOSR was determined for Eastern, SD (conventional tillage, humid climate) and Western and Central SD (no-till, semi-arid climate) by averaging yield data within agro-environments. EOSR is described as the seeding rate at which planting additional seed results in a yield increase great enough to pay for the additional seed planted; in short, EOSR is the seeding rate that produces the greatest dollar return to seed and is a valuable tool to maximize price margins for producers. For the EOSR analysis, prices of *B. carinata* (.411 \$ kg^{-1}) and cost of 1000 *B. carinata* seeds (.0016\$) were used (Sitter, 2017). EOSR can be calculated using the polynomial equation formed when plotting seed yield (kg ha^{-1}) against seeding rate (kg ha^{-1}). EOSR can then be calculated using the polynomial equation along with current cost of seed (\$ kg^{-1}) to solve the following formula:

Equation 1.1. Economic Optimum Seeding Rate (EOSR) for *B. carinata*.

$$EOSR = \frac{\frac{\$/\,1000\; seeds\; B.carinata}{\$\;/\;\mathrm{kg}\; B.carinata} - b}{2\; \times c}$$

Where:

\$/1000 seeds = Cost of 1000 seeds of *B. carinata*

\$/kg carinata= Selling price of *B. carinata* seed

b= Amount of increase or decrease (slope) in seed yield in response to seed rate

c= Y-intercept, the expected yield when seeding rate is 4 kg ha^{-1}

RESULTS

Rainfall accumulation and temperature data were collected throughout the growing period for all environments (Tables 1.2 and 1.3). The weather data was collected via weather stations managed by the South Dakota Agricultural Experiment Station located at each site. At Brookings in 2016, rainfall totals were much greater than the 30-year average. While early season precipitation followed long-term trends, excessive rainfall in the months of July and August caused prolonged periods of water-logged conditions during seed fill and dry-down periods. The average mean temperatures at Brookings in 2016 were slightly higher than the 30-year average (>1ºC) throughout the growing season for all months except July and August. Maximum temperatures often reached excesses of 25 ºC, but rarely exceeded 30 ºC during the critical growth stages (flowering and seed-fill) which occur during June and July (Table 1.4). Additionally, rainfall events occurred regularly during the critical growth stages; however, a 10-day period in which no rainfall events occurred was observed in late June (Table 1.4). At Brookings in 2017, rainfall totals were greater than the long-term average by ~50 mm. The month of June exhibited severe drought conditions, with only 5 mm of total precipitation (Table 1.4). Excessive late season rainfall totals in July and August alleviated the drought conditions seen during the seed-fill period and brought rainfall totals for the growing season within the normal range. Mean temperatures at Brookings in 2017 similar to the long-term average throughout the growing season except for July and August; mean temperatures in July were 1.7 ºC warmer than the long-term average with daily maximum temperatures regularly exceeding 30 ºC (Table 1.4).

At Pierre in 2016, April rainfall totals were double the long-term average, but drought conditions were seen throughout May and June; during this 2-month period, rainfall totals were less than half of the long-term average. Drought conditions were slightly alleviated in July, but rainfall totals were still significantly lower than the long-term average (Table 1.2). Average temperatures were close to the long-term average for all months except June which exhibited temperatures 2°C above the long-term average; these above average temperatures occurred during the seed-filling period (Table 1.4). At Pierre in 2017, substantially lower rainfall totals were recorded during the months of May and June; additionally, only 1.5 mm of rain was recorded during the month of July (Table 1.2). Mean temperatures at Pierre in 2017 were warmer than the average for the months of May, June, and July with values of +0.7, +1.6, and +2.2°C, respectively (Table 1.3). During the month of July, maximum temperatures exceeded 30°C every day; the high temperatures during the critical growth stages coupled with substantially lower rainfall totals brought Pierre into a severe drought during the growing season (Table 1.5).

At Ideal in 2017, rainfall totals in the months of April and May were both below the long-term average with the months of June and July bringing a total of only 12.8 mm rainfall over that period (Table 1.3). Drought conditions were alleviated in August with rainfall totals substantially greater than the long-term average (Table 1.2). Average and maximum temperatures throughout the growing season were higher than the long-term values for all months except for the month of August, which was slightly cooler than the long-term average. The average temperatures for the months of April, May, June and July, and August were higher than the long-term average by values of 1.3, 0.5, 2.1, and 3.6°C, respectively. Maximum temperatures throughout critical growth periods of June and July were substantially higher than normal, by values of 3.9 and 5.5°C, respectively

(Table 1.3). The warmer temperatures and reduced rainfall throughout this period resulted in severe drought conditions throughout the growing season (Table 1.6).

The number of established plants increased significantly with increasing seeding rate at all environments ($P \leq .05$) (Tables A.2-A.6). Differences in stand establishment at Brookings and Pierre were evident (Figure 1.1 and 1.2.) For all environments, the lowest number of established plants was observed in the 4.5 kg ha^{-1} seeding rate while the greatest number of established plants was observed in the 18 kg ha^{-1} seeding rate. The number of established plants was greatest in Brookings in 2016, (79-179 plants m^{-2}) and lowest at Pierre in 2017 (15-45 plants m^{-2}) (Table 1.7 and Table 1.10). At both Brookings and Pierre, stand establishment was reduced in 2017 compared to 2016 (Tables 1.7-1.10). At all environments except Brookings in 2017, variety did not have a significant influence on the number of established plants; in this environment, the variety “M01” outperformed “A120,” resulting in greater plant stands across all seeding rates with values of 73 and 61 plants m^{-2}, respectively.

For all environments, plant height decreased significantly with increasing seeding rate ($P \leq .05$) (Tables A.2-A.6); tallest plants were observed in the 4.5 kg ha^{-1} seeding rate and shortest plants were observed in the 18 kg ha^{-1} seeding rate for all environments. *Carinata* plants were tallest at Brookings in 2016 (108-119 cm) and shortest plants at Pierre in 2017 (64-71 cm) (Table 1.7 and Table 1.10). At both Brookings and Pierre, plants were shorter in 2017 when compared to 2016 (Table 1.7-1.10). For all environments except Ideal in 2017, variety did not significantly influence plant height. At Ideal, variety “A120” (74 cm) had significantly taller plants compared to “M01” (67 cm) across all rates (Table 1.8).

Lodging severity was significantly influenced by seeding rate at all environments with lodging severity increasing with increasing seeding rate ($P \leq .05$) (Tables A.2-A.6). At all environments except Pierre in 2017, lodging was least severe in the lowest seeding rate of 4.5 kg ha^{-1} and most severe in the 18 kg ha^{-1} rate (Table 1.10). The most severe lodging was observed in Brookings in 2016 ranging from 4.6 at the lowest seeding rate to 8.6 in the highest seeding rate. Lodging was less severe across all seeding rates at Brookings in 2017 compared to 2016 (Table 1.7 and 1.8); lodging severity across all rates was comparable at Pierre in both 2016 and 2017 (Table 1.9 and 1.10). At Pierre in 2017, lodging severity in the 4.5, 9, and 13.5 kg ha^{-1} rates were not significantly different (Table 1.10.). Lodging severity was not influenced by variety across all environments.

Pod shatter decreased significantly with increasing seeding rates at all environments except Ideal in 2017 (Table 1.11). Pod shatter was greatest at the lowest seeding rate (4.5 kg ha^{-1}) and lowest in the highest seeding rate (18 kg ha^{-1}) at all locations. Additionally, pod shatter was greatest Pierre in 2017 (11-21%) and lowest at Brookings in 2017 (4-7%) (Table 1.8 and 1.10). At Pierre in 2016, the variety "A110" exhibited significantly greater pod shatter (13%) compared to "A120" (10%) across all seeding rates (Table 1.9). The number of pods $plant^{-1}$ was significantly influenced by seeding rate across all environments ($P \leq .05$) (Tables A.2-A.6).

Pods $plant^{-1}$ decreased significantly with increasing seeding rate for all environments except Brookings and Pierre in 2017 (Table 1.8 and 1.10). The greatest number of pods $plant^{-1}$ was observed at Pierre in 2017 (130-190) (Table 1.10); meanwhile, the lowest number of pods $plant^{-1}$ was observed at Brookings in 2016 (48-82) (Table 1.7). At both Brookings and Pierre, the number of pods $plant^{-1}$ were greater in

2017 compared to 2016 (Table 1.7-1.10). Variety did not have a significant impact on pods plant^{-1} for all environments except Ideal in 2017, with “A110” producing more pods plant^{-1} than “M01” with values of 79 and 64, respectively when averaged across all seeding rates (Table 1.11).

Combined analysis showed that seeding rate did not influence the number of seeds pod^{-1}; however, number of seeds pod^{-1} was influenced by environment (P≤.05) (Table A.1). The greatest number of seeds pod^{-1} occurred at Pierre in 2016 (17), while the lowest number of seeds pod^{-1} was observed at Pierre in 2017 (14) (Table 1.9 and 1.10). Pierre and Ideal in 2017 exhibited lower seeds pod^{-1} than all other environments with average values of 11 and 14, respectfully (Table 1.10 and 1.11). Variety did not influence seeds pod^{-1} for all environments except Ideal in 2017; variety “A120” produced more seeds pod^{-1} than “M01” with values of 15 and 13, respectively.

Days to flowering and days to maturity were evaluated at Brookings in 2016 and 2017; no other environments were evaluated for these agronomic traits. Seeding rate had a variable influence on days to flowering according to environment. In 2016, days to flowering was not influenced by any of the main effects or their interactions; days to flowering for all treatments was ~54 days (Table 1.7). In 2017 (P≤.001), days to flowering increased with increasing seeding rate (Table 1.8); the longest days to flowering was observed in the 18 kg ha^{-1} rate and the lowest days to maturity was observed in the 4.5 kg ha^{-1} rate with values of 63 and 59 days, respectively. At Brookings, days to maturity was influenced by seeding rate (P≤.001) and variety (P≤.001) (Tables A.2 and A.3). Days to maturity increased with increasing seeding rate (Table 1.7); the longest days to maturity was observed in the 18 kg ha^{-1} rate and the least days to maturity was observed in the 4.5 kg ha^{-1} rate with values of 95 and 92 days, respectively. Across all seeding rates, variety "A110" took longer to mature compared to "A120" by ~2 days. In 2017, days to maturity was influenced by seeding rate ($P \leq .001$) (A.3). Days to maturity increased with increasing seeding rate (Table 1.8); the longest days to maturity was observed in the 18 kg ha^{-1} rate and the shortest days to maturity was observed in the 4.5 kg ha^{-1} rate with values of 99 and 94 days, respectively.

Seeding rate significantly influenced seed yield for all environments ($P \leq .05$) (Tables A.2-A.6). At all environments except Brookings in 2017, seed yield increased with increasing seeding rate in a curvilinear manner before tapering off, although the seeding rate at which yields were optimized varied depending on environment (Figure 1.3). Optimal yields were observed in the 13.5 kg ha^{-1} seeding rate (1492 kg ha^{-1}) and 9 kg ha^{-1} rate (1140 kg ha^{-1}) at Brookings in 2016 and 2017, respectively (Table 1.7 and 1.8). Importantly, at Brookings in 2016, yields in the 9 and 13.5 kg ha^{-1} rates were not significantly different. In a similar manner, yields in the 4.5 and 9 kg ha^{-} rates were not significantly different at Brookings in 2017. At Pierre in 2016 and Ideal in 2017, optimal yields were obtained in the 13.5 kg ha^{-1} rate with values of 741 and 408 kg ha^{-1}, respectively. At Pierre in 2017, yield data was not collected due to severe drought conditions and lack of seed-fill. The greatest yields were obtained at Brookings in 2016 (1156-1492 kg ha^{-1}) and the lowest yields were observed at Ideal in 2017 (252-408 kg ha^{-1}) (Table 1.7 and 1.11).

For all environments except Brookings in 2016, seed yield was not influenced by variety. In Brookings in 2016, "A120" outperformed "A110" across all seeding rates with values of 1422 and 1188 kg ha^{-1}, respectively (Table 1.7). Economic Optimum Seeding

Rate (EOSR) of *B. carinata* was then determined using average seed yield data obtained in 2016 and 2017. Separate EOSR's were obtained according to production system in South Dakota: East River (Brookings- temperate, conventional tillage) and Central and West River (Pierre and Ideal- semi-arid, no-till). EOSR for Brookings (conventional tillage, humid-temperate climate) was determined to be ~10.1 kg ha^{-1} which resulted in yields of ~1232 kg ha^{-1}. EOSR for Pierre and Ideal (no-till, semi-arid) was determined to be ~13 kg ha^{-1} which resulted in yields of ~393 kg ha^{-1} (Figure 1.2).

Oil concentration was significantly influenced by environment and seeding rate by environment interaction ($P \leq .05$) (Table A.1) meaning oil concentration response to seeding rate was variable according to environment. Oil concentration was greatest at Brookings in 2017 (272-397 g kg^{-1}) and lowest at Ideal in 2017 (291-334 g kg^{-1}) (Table 1.7 and 1.11). At Brookings in 2016 and 2017, differences in oil concentration among seeding rates were not significant (Table 1.7 and 1.8). At Pierre in 2016, oil concentration increased with increasing seeding rate with optimal oil concentrations being observed in the 13.5 kg ha^{-1} treatment with an average value of 330 g kg^{-1} (Table 1.9). Similarly, at Ideal in 2017 oil concentration increased with increasing seeding rate, with optimal oil concentrations being observed in the 18 kg ha^{-1} treatment with an average value of 330 g kg^{-1} (Table 1.11). For all environments except Brookings in 2017, variety did not have a significant effect on oil concentration. At Brookings in 2017, variety "A120" produced seed with greater oil concentration compared to "M01" with values of 417 and 363 g kg^{-1}, respectively.

The influence of seeding rate, environment, variety, and seeding rate by environment interactions on seed oil yield were significant ($P \leq .05$) (Table A.1). Seed oil yield response to seeding rate was variable across environments. Seed oil yield was greatest at Brookings in 2016 (385-517 g kg^{-1}) and lowest at Ideal in 2017 (73-124 g kg^{-1}) (Table 1.7 and 1.11). At Brookings in 2016, seed oil yield increased with increasing seeding rate up the 13.5 kg ha^{-1} seeding rate before decreasing (Table 1.7). Conversely, oil yields at Brookings in 2017 decreased with increasing seeding rate; optimal oil yields were obtained in the 4.5 kg ha^{-1} rate with average values of 439 kg ha^{-1}, however differences were not significant (Table 1.8). At both Pierre in 2016 and Ideal in 2017, seed oil yield increased with increasing seeding rate. At Pierre in 2016, optimal oil yields were obtained in the 9 kg ha^{-1} rate (251 kg ha^{-1}) while optimal oil yields were obtained in the 13.5 kg ha^{-1} rate (124 kg ha^{-1}) at Ideal in 2017 (Table 1.10 and 1.11).

DISCUSSION

The objective of this research was to i) evaluate the response, in seed yield and other agronomic traits, of two *B. carinata* varieties to four different seeding rates, ii) determine if variety x seeding rate interactions occurred, and iii) determine the seeding rate for economic optimum yield at two agro-environments in South Dakota. Differences in environmental conditions and tillage practices will provide an opportunity to determine the optimum seeding rate to be used at each location and tillage system to be factored into a best management practice manual.

Recommended plant population for *B. carinata* production in the NGP are in the range 86 to 183 plants m^{-2} (Agrisoma 2015). In this study, stand establishment varied greatly in response to seeding rates and environments. Plant populations at Brookings in 2016 (79-179 plants m^{-2}) were within the recommendations for all seeding rates except

4.5 kg ha^{-1}. At Brookings in 2017, plant populations (37-96 plants m^{-2}) were lower than the recommendations for all treatments except the 18 kg ha^{-1} seeding rate. Reduced plant stands in 2017 are likely due to the lighter textured soils as well as dry and cool conditions at planting which delayed seedling germination and emergence. Lighter textured soils have reduced water holding capacity and are thus less able to withstand dry periods (Brown et al., 2008; Grady, 2002). Improved stand establishment across all treatments at Brookings in 2017 for "M01" suggest potential cold and drought tolerant qualities which makes the variety better suited to dry regions. Stand establishment at Pierre in 2016 and 2017 and Ideal in 2017 were well below the recommendations for *B. carinata* production in the NGP across all seeding rates. The extreme levels of variation seen in stand establishment across environments and years is due to two major factors: climatic conditions (semi-arid vs humid temperate) and management practices (no-till vs conventional tillage) which have significant impacts on stand establishment and development (CCC 2016). Reductions in stand establishment for *B. carinata* have been observed in semi-arid environments (Punia et al., 2001).

The Brookings environments (humid temperate, conventional till) resulted in greater number of established plants than the Pierre and Ideal environments (semi-arid, no-till). Conventional tillage practices followed using a roller, can be used to flatten the soil to create a firm seed bed; a firm seed bed encourages even plant emergence and growth (Godsey et al., 2013). Conversely, in no-till systems variation in amount of residue can result in uneven emergence and stand development. This uneven emergence was observed at Pierre in both 2016 and 2017 where corn was the previous crop. Uneven residue distribution across plots resulted in large variation in stand establishment within the plot area (Figure 1.1 and 1.2). At Ideal in 2017, the previous crop was soybean; soybean residue breaks down quickly which improves uniformity of residue distribution within the plots, so these effects were not observed at Ideal. Additionally, no-till systems that contain large amounts of crop residue can lower temperatures in the topsoil during the spring resulting in reduced germination and uniformity of plant development (Godsey et al., 2013). In environments with large amounts of crop residue, the grain drill may not be able to properly cut through the residue and place the seed at the optimal depth; the reduction in seed-soil contact can potentially result in seed drying out due to lack of adequate soil moisture. (Godsey et al., 2013); use of heavier drills in commercial production may help to mitigate this effect and improve seedling establishment in no-till, high residue systems.

In agreement with previous studies done on canola, *B. carinata* plant height decreased with increasing seeding rate (Khan et al., 2017; Inamullah et al., 2013). Across all environments, the lowest seeding rate (4.5 kg ha^{-1}) produced the tallest plants. Plants were taller at Brookings in 2016 than those at Brookings in 2017 despite similarities in soil characteristics and climatic conditions. These differences can likely be explained by the cooler temperatures and periods of minimal rainfall during seeding at Brookings in 2017 which delayed plant emergence and development (Cardone et al., 2002). Despite the overall decrease in plant heights at Brookings in 2017 compared to 2016, the negative correlation between seeding rates and plant height remained intact. Overall, plants at Pierre and Ideal were shorter than plants at the Brookings location. This is likely due to differences in climatic conditions (temperature and rainfall) that are associated with semi-arid environments. Plants at Pierre and Ideal in 2017 were considerably shorter than

Pierre in 2016 despite the very similar environments due to the severe drought conditions that plagued the region during the growing season in 2017. Importantly, the negative effect of seeding rate on plant height remained intact despite drought conditions.

As previously reported in rapeseed, lodging severity increases with increasing seed rate (Khan et al., 2017; Bilgili et al., 2003). Despite the significant differences in plant height across environments, lodging severity was strongly associated with plant height as previously reported (Pan et al., 2012; Wright et al. 1988). The extreme lodging observed in Brookings in 2016 was due to favorable growing conditions at seeding and early plant development resulting in tall, vigorous plants. This was followed by a mid-season wind/hail storm (80+ kph) on June 17th (post-flowering) and late-season rains during pod fill (late July-early August) creating conducive conditions for lodging. Periods of severe rainfall post-flowering with water-logged soil have been shown to cause severe lodging in *B. carinata* (Zanetti et al., 2006). Although extensive late-season rains also occurred in 2017, reductions in plant height may have mitigated lodging severity. At Pierre and Ideal in 2017, lodging was less prevalent; reductions in plant populations associated with no-till environments due to uneven emergence have been known to correspond to increase branching in canola (Harker et al., 2012; Godsey et al., 2013). Increased branching (primary and secondary) is believed to help mitigate lodging severity, even in environments such as Pierre and Ideal which experience consistently windy conditions. Thus, the influence of seeding rate on plant height and lodging should be taken into consideration in environments in which lodging is a potential problem; high plant populations and excessive late-season rainfall accumulation promote lodging and may require reductions in seeding rates in order to reduce potential yield losses.

Days to flowering increased with increasing seeding rate at Brookings in 2017. However, days to flowering was not influenced by seeding rate at Brookings in 2016 which is in agreement with previous research done on *B. napus* (Degenhardt and Kondra, 1980). These results confirm that seeding rate has a variable impact on days to flowering (Harker et al., 2012). In some reports, flowering has been delayed with increasing seeding rates due to the increased competition between individual plants, forcing maturity to be delayed and development to be uneven. Production of *B. carinata* in the NGP often requires earlier flowering as a means of avoiding the high temperatures that are associated with the region in July; reaching the flowering period earlier and extending the flowering period itself have been shown to increase yield and may be a key to effectively produce *B. carinata* in the region and maintain yield goals.

Days to maturity increased with increasing seeding rate at Brookings in 2016 and 2017 Table 1.7 and 1.8). The days to maturity are close to or slightly less than those in previous reports (101-108 days) (Getinet et al., 1995). Delayed maturity in 2017 compared to 2016 may be a result of cool temperatures and dry conditions at seeding resulting in delayed emergence and plant development. These results confirm findings from previous studies which suggest that increased seeding rates can result in delayed maturity, which is most likely explained by prolonged periods of vegetative growth (Inamullah et al., 2013). Delaying maturity may be beneficial to optimize yields in some environments, but is most likely not a suitable alternative for producers in the NGP due to the high temperatures and drought stress which often occur during critical growth stages (flowering and seed-fill) for determining yield potential. Thus, delaying maturity may not be a realistic option; instead, early seeding and flowering may avoid unfavorable conditions and increase yields as in other *Brassica spp* (Kirkland Johnson, 2000).

Pod shatter (%) decreased as seeding rates increased across all environments. The greatest amount of pod shatter was observed in the lowest seeding rate while the lowest pod shatter was observed in the higher rates. This suggests that increasing seeding rate can result in slight decreases in pod shatter. This association is most likely explained by the influence that seeding rate has on days to maturity. Increasing seeding rate may result in delayed maturity, thus decreasing the period where mature pods are exposed to hot and dry conditions which promote shattering. Pod shatter at Brookings in 2016 was slightly higher than in 2017 due to prolonged periods of late-season rains that delayed dry-down and harvest time resulting in increased prevalence of pod shatter. The Pierre location exhibited greater pod shattering than the Brookings location. The differences can most likely be explained by the vast differences in climates of these two locations. Pierre (semi-arid) exhibits higher temperatures, lower rainfall totals, and higher wind speeds than the Brookings (humid temperate) location during the seed fill and dry-down periods. These prolonged hot and dry periods during seed-fill and dry down periods in combination with excessive wind speeds have been known to promote shattering in canola (CCC 2016).

As with plant height, the number of pods plant^{-1} decreased with increasing seeding rate, with substantial variation occurring across environments. Planting *B. carinata* with lower seeding rates (~4.5 kg ha^{-1}) reduces intraspecific competition and allows for more even growth and development among plants. Additionally, lower seeding rates have been shown to result in the production of more vigorous plants and reduce lodging prevalence and severity; plants are able to develop stronger stems, additional lateral branches, and more siliques, resulting in greater yields (Bilgili et al., 2003). Despite the risk of reduced ground cover that is associated with low seeding rates, *B. carinata* has been shown to regulate vegetative propagation through the increased production of lateral branches as a compensatory mechanism (Angadi et al., 2003). Low seeding rates promote uniform development throughout the plant, which to strengthen the stems and reduce lodging severity; low seeding rates promote the production of siliques on the lower branches, increasing stability and reducing the impact of environmental stresses in adverse conditions (Sarkees, 2013). On the contrary, as seeding rates increase (>12 kg ha^{-1}), intraspecific competition is increased; increased competition results in small, weak plants with fewer secondary branches and reduction in the number of siliques (Angadi et al., 2003; Leach et al., 1999). Despite an overall decrease in pod number at higher plant densities, *Brassica* species exhibit a greater number of siliques on the upper portion of the plant increasing the potential for lodging.

The number of seeds pod^{-1} was not significantly influenced by seeding rates though there was a trend towards reduction in seeds pod^{-1} with increasing seeding rate. The number of seeds pod^{-1} varied according to environment. Brookings experiences higher rainfall totals and cooler temperatures than Pierre and Ideal on average; importantly, Pierre and Ideal in 2017 experienced severe drought conditions throughout much of the growing season, in particular the flowering and seed-fill periods resulting in suboptimal plant development and maturity. Drought during these critical growth stages has been known to reduce the number of seeds pod^{-1} in canola (Mirzaei et al., 2013).

Data analysis revealed that seed yield increased in a curvilinear fashion with increasing seeding rate for all locations except Brookings in 2017. This curvilinear relationship is due to the decrease of resource use efficiency (water and nutrients) with increasing seeding rate (Khan et al., 2017). Seed yield is a function of the effects and interactions of many genetic and environmental factors including: temperature, moisture, tillage practices, population density, number of pods plant^{-1}, number of seeds pod^{-1}, and seed weight (Chen et al., 2005). Optimal yields occurred at a seeding rate of 13.5 kg ha^{-1} for all locations except Brookings in 2017 which observed optimal yields at the of 9 kg ha^{-1} rate. However, the seeding rates which showed optimal yields were often not significantly different than lower seeding rates at each environment; these results agree with previous research which has shown that *Brassica* species have great yield plasticity. This yield plasticity is due to the compensatory branching ability in response to environmental conditions such as lower plant populations; however, yield response varies by year and location due to the many factors responsible for yield (Chen et al. 2005; Pan et al., 2012). The results of EOSR analysis determined that optimal seeding rates for the Eastern, SD (Brookings) and Western and Central, SD (Ideal and Pierre) are ~10 and ~13 kg ha^{-1}, respectively. These results show that greater seeding rates should be used in the semi-arid regions of the NGP to help compensate for lower stand establishment and yield reductions due to climatic conditions (high temperatures and low rainfall).

Seed oil concentration responded variably in each environment with increasing seeding rate, supporting previous research (Gan et al., 2015; Van Deynze et al., 1992; Sharkees, 2013). Oil concentrations were on par with or slightly lower than oil concentrations previously reported for *B. carinata* (Cardone et al., 2002). The response of oil concentration to seeding rate was determined significantly by the environmental conditions (humid temperate vs semi-arid). Oil concentrations at Brookings (humid temperate) were much greater than oil concentrations at Pierre and Ideal (semi-arid). Low oil concentrations at Pierre and Ideal were most likely due to low precipitation totals throughout the growing season; this coupled with high temperatures have been shown to be directly responsible for lower oil concentration in *Brassica* species (Wright et al., 1998; Gan et al., 2007). Low oil concentration in semi-arid environments is likely due to accelerated growth and short growing season which negatively impact proper seed maturity and oil accumulation (Getinet et al., 1995).

Total seed oil yield also responded variably in response to increasing seeding rate depending on environment. At all environments, except Brookings in 2017, total oil yields increased in a curvilinear manner with increasing seeding rate; this relationship is similar to the effect of seeding rate on seed yield. While oil yields varied considerably with environment, values are within the ranges reported in other studies which show oil yields ranging from 185-998 kg ha^{-1} for all environments except Ideal and Pierre in 2017 (Pan et al., 2012; Getinet et al., 1995). The Brookings environments in 2016 and 2017 had significantly greater seed oil yield compared to Pierre and Ideal. Warmer temperatures during seed filling have a negative effect on seed oil content (Pan et al., 2012; Faraji, 2012; Canola Watch, 2016). Higher temperatures and lower precipitation totals were observed at critical growth stages in Pierre and Ideal, contributing to lower oil yields. Overall, total oil yield was optimized at lower seeding rates (4.5-13 kg ha^{-1}) at Brookings while optimal oil yields at Pierre and Ideal were found in the higher seeding rates (9-18 kg ha^{-1}).

CONCLUSIONS

The results of EOSR analysis determined that optimal seeding rates for *B. carinata* are ~10 and ~13 kg ha^{-1} for Eastern, SD (Brookings) and Western and Central, SD (Ideal and Pierre), respectively. This indicates that that higher seeding rates may be required in the semi-arid regions of the NGP to help compensate for lower stand establishment and yield reductions due to harsh climatic conditions (high temperatures and low precipitation totals). The results regarding seed yield and oil yield show that *B. carinata* is more suited to the humid temperate climates of South Dakota, but may still be productive in the semi-arid environments if conditions are conducive. Use of supplemental irrigation in the semi-arid regions to compensate for periods of severe drought during the flowering and seed filling periods may provide a potential option for *B. carinata* production in these regions. In addition, development of varieties with early flowering periods, prolonged flowering periods, and earlier maturing dates may help to reduce the yield penalty. In cases where that oil concentration does not meet the required thresholds selling seed for meal for use or for industrial applications may be an alternative option.

REFERENCES

Agriculture Victoria. 2012. Growing Canola. Department of Environment and Primary Industries. http://agriculture.vic.gov.au/agriculture/grains-and-other-crops/crop-production/growing-canola (Accessed 11 November 2017).

Agrisoma 2015. Resonance Carinata 2015 Production Manual- A guide to best management practices. Agrisoma. 1-18

Angadi, S.V., H.W. Cutforth, B.G. McConkey, and Y. Gan. 2003. Crop ecology, management, and quality. Yield adjustment by canola grown at different plant populations under semi-arid conditions. Crop Sci. 43: 1358-1 366.

Bilgili, U., M. Sincik, A. Uzun, and E. Acikgoz. 2003. The influence of row spacing and seeding rate on seed yield and yield components of forage turnip (*Brassica rapa* L.) J. Agron. Crop Sci. 189 (4): 250-254.

Brown, J., J.B. Davis, M. Lauver, and D. Wysocki. 2008. Canola Growers' Manual. United States Canola Association. 1-71.

Canola Council of Canada. 2016. Harvest management. CCC. http://www.canolacouncil.org/canola-encyclopedia/managing-harvest/harvest-management/. (Accessed 11 November 2017).

Canola Council of Canada. 2016. Crop nutrition. CCC. https://www.canolacouncil.org/canola-encyclopedia/crop-nutrition/crop-nutrition/. (Accessed 11 November 2017).

Canola Watch. 2016. 7 causes for missing pods. Canola Watch. http://www.canolawatch.org/2016/06/23/7-causes-for-missing-pods/. (Accessed 11 November 2017).

Cardone, M., M.V. Prati, V. Rocco, M. Seggiani, A. Senatore, and S. Vitoloi. 2002. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: engine performance and regulated and unregulated exhaust emissions. Environ. Sci. Technol. 36(21): 4656-4562.

Chen, C., G. Jackson, K. Neill, D. Wichman, G. Johnson, and D. Johnson. 2005. Determining the feasibility of early seeding canola in the Northern Great Plains. Agron. J. 97: 1252-1 262.

Degenhardt, D.F., and Z.P. Kondra. 1980. The influence of seeding date and seeding rate on seed yield and growth characters of five genotypes of *Brassica napus*. J. Plant. Sci. 61:185-190.

Gan, Y.K., K.N. Harker, H.R. Kutcher, R.H. Gulden, B. Irvine, W.E. May, and J.T. O'Donovan. 2015. Canola seed yield and phenological responses to plant density. Can. J. Plant Sci. 96(1): 151-1 59.

Gan, Y.K., Malhi, S.S., Brandt, S., Katepa-Mupondwa, F., and Kutcher, H.R. 2007. *Brassica juncea* canola in the Northern Great Plains: responses to diverse environments and nitrogen fertilization. Agron. J. 99:1208-1218.

Gan, T., S.V. Angadi, H. Cutforth, D. Potts, V.V. Angadi, and C.L. McDonald. 2004. Canola and mustard response to short periods of temperature and water stress at different developmental stages. Can. J. Plant Sci. 84: 697-704.

Getinet, A., G. Rakow, R.K. and Downey. 1995. Agronomic performance and seed quality of Ethiopian Mustard in Saskatchewan. Can. J. Plant Sci. 76:387-392.

Godsey, C., R. Taylor, and M. Boyles. 2013. No-till winter canola considerations. Oklahoma Cooperative Extension Service. PSS-2153.

Grady, K. 2002. Canola production. South Dakota State Cooperative Extension Service. ExEx 8130.

Hanson, B.K., B.L. Johnson, R.A. Henson, and N.R. Riveland. 2008. Seeding rate, seeding depth, and cultivar influence on spring canola performance in the Northern Great Plains. Agron. J. 100: 1339-1 345.

Harker, K.N., J.T. O'Donovan, T.K. Turkington, R.E. Blackshaw, N.Z. Lupwayi, E.G. Smith, H. Klein-Gebbinck, L.M. Dosdall, L.M. Hall, C.J. Willenborg, H.R. Kutcher, S.S. Malhi, C.L. Vera, Y. Gan, G.P. Lafond, W.E. May, C.A. Grant, and D.L. McLaren. 2012. High-yield no-till canola production on the Canadian prairies. Can. J. Plant Sci. 92:221-233.

Holzapfel, C. and W. May. 2015. Investigating wider row spacing in no-till canola: implications for weed competition, response to nitrogen fertilizer, and seeding rate recommendations (2013-2016). Final Project Report for the Saskatchewan Canola Development Commission.http://www.saskcanola.com/quadrant/System/research/reports/Holzapfel.CARP-SCDC2012-4.Long_Report.pdf. (Accessed 17 November 2017).

Inamullah, B.K., D. Miftahud, M. Siddiq, A. Ali Khan, A., Munir, K. Azeem, and G. Ul-haq. 2013. Effect of various seed rates and nitrogen levels on the productivity of late sown *Brassica*. Sarhad J. Agric. 29: 503–509.

Khan, S., S. Anwar, J. Kuai, S. Ullah, S. Fahad, and G. Zhou. 2017. Optimization of nitrogen rate and planting density for improving yield, nitrogen use efficiency, and lodging resistance in oilseed rape. Front. Plant Sci. 8(532): 1-9.

Kirkland, K.J., and E.N. Johnson. 2000. Alternative seeding date (fall and April) affect *Brassica napus* canola yield and quality. Can. J. Plant Sci. 80: 713-719.

Kutcher, K.M., H.R. Kirkland, and E. Johnson. 2000. Effect of early spring seeding on diseases of canola. University of Saskatchewan Soils & Crops. http://www.usask.ca/soilsncrops/conference-proceedings/previous_years/Files/2000/2000docs/167.pdf. (Accessed 17 November 2017).

Leach, J.E., H.J. Stevenson, A.J. Rainbow, and L.A. Mullen. 1999. Effects of high plant population on the growth and yield of winter oilseed rape (*Brassica napus*). J. Agric. Sci. 132: 173-1 80.

Ma, B.L., Z. Zheng, A. Caldwell, A. Mills, E.H. Vanasse, P. Scott, and D.L. Smith. 2016. Optimizing seeding dates and rates for canola production in the humid eastern Canadian ecosystems. Agron. J. 108:1869-1 879.

Mckenzie, R.H., E. Bremer, A.B. Middleton, P.G. Pfiffner, and S.A. Woods. 2011. Effect of seeding date and rate for irrigated grain and oilseed crops in southern Alberta. Can. J. Plant Sci. 91:293-303.

Mekonnen, T.W., A. Wakjura, and T. Genet. 2014. Genotypic variability, heritability, and genetic advance in Ethiopian Mustard (*Brassica carinata* A. Braun.) genotypes at northwestern Ethiopia. J. Plant Breed. Genet. 02(03):109-114

Mirzaei, A., R. Naseri, A. Moghadam, and M. Esmailpour-Jahromi. 2013. The effects of drought stress on seed yield and some agronomic traits of canola cultivars at different growth stages. Bull. Env. Pharmacol. Life Sci. 2 (11):115-121.

Morrison, M.J., P.B.E. Mcvetty, and R. Scarth. 1990. Effect of altering plant densities on summer rape. Can. J. Plant Sci. 70:139-1 49.

Pan, X., C.D. Caldwell, K.C. Falk, and R. Lada. 2012. The effect of cultivar, seeding rate, and applied nitrogen on *Brassica carinata* seed yield and quality in contrasting environments. Can. J. Plant Sci. 92: 961-971.

Potter, T.D., J.R. Kay, and I.R. Ludwig. 1998. Effect of row spacing and sowing rate in canola cultivars in low rainfall areas. Australian Oilseeds Federation. http://www.australianoilseeds.com/__data/assets/pdf_file/0013/4513/Row_spacing_and_sowing_rate_in_low_rainfall_SA.pdf. (Accessed 17 November 2017).

Punia, S.S., S. Chahar, and S.K. Agarwal. 2001. Influence of crop geometry and nitrogen on seed yield and yield attributes of Ethiopian mustard (*Brassica carinata*) Indian J. Agron. 46:732-735.

Rakow, G., J.P. Raney, and J. Relf-Eckstein. 2004. *Brassica* (canola) oilseed breeding in Canada. Agriculture and Agri-Food Canada. http://gcirc.org/fileadmin/documents/Bulletins/B22/B22_12.pdf. (Accessed 17 November 2017).

Sarkees, N.A. 2013. Response of growth, yield, and oil of rapeseed to sowing method and seeding rate. IOSR-JAVS. 3(1): 1-6.

Seepaul, R., D.L. Wright, C.M. Bliss, S. George, and J.J. Marois. 2014. The effects of planting date and N application rate on *Brassica carinata* production in north Florida. North Florida Research and Education Center. ASA-CSSA-SSSA 2014 Annual Meeting.

https://dl.sciencesocieties.org/publications/meetings/download/pdf/2014am/87656. (Accessed 17 November 2017).

Sitter, T. 2017. Personal communication. Northern Plains Commodities, LLC. August 8 2017.

Van Deynze, A.E., P.B.E. Mcvertty, R. Scarth, and S.R. Rimmer, 1992. Effect of varying seeding rates of hybrid and conventional summer rape performance in Manitoba. Can. J. Plant Sci. 27: 635-641.

Wright, G. C., C.J. Smith, and M.R. Woodroffe. l998. The effect of irrigation and nitrogen fertilizer on rapeseed (*Brassica napus*) production in south-eastern Australia. Irrig. Sci. 9: l-13.

Zanetti, F., T. Vamerali, S. Bona, and G. Mosca, 2006. Can we “cultivate” erucic acid in Southern Europe? Ital. J. Agron.1: 3-10.

Table. 1.1. Soil physical and chemical characteristics for all environments.

Location	Year	Previous Crop	Depth (in)	Texture Class	pH	Soluble Salts (mmho/cm)	Organic Matter (%)	Nitrogen-NO3 (ppm)	Olsen-P (ppm)	K (ppm)
Brookings	**2016**	**WW**	**0-6**	**Medium**	**5.6**	**0.1**	**4.8**	**12.0**	**16.0**	**349.0**
Brookings	**2017**	**WW**	**0-6**	**Medium**	**5.6**	**0.1**	**4.7**	**10.0**	**10.0**	**141.0**
Pierre	**2016**	**Corn**	**0-6**	**Medium**	**6.1**	**0.2**	**3.0**	**10.1**	**21.7**	**626.0**
Pierre	**2017**	**Corn**	**0-6**	**Medium**	**7.2**	**0.6**	**3.3**	**14.5**	**21.5**	**510.0**
Ideal	**2017**	**Soybean**	**0-6**	**Medium**	**7.6**	**0.6**	**3.4**	**17.0**	**17.0**	**384.0**

WW = Winter Wheat

Table. 1.2. Monthly rainfall data collected throughout the growing period (GP) for all environments (2016 and 2017) in South Dakota (numbers in parentheses indicate differences from 1981-2010 average).

	April	*May*	*June*	*July*	*August*	*Total GP Rainfall*
Rainfall (mm)						
Brookings 2016	**38.1 (-16.0)**	**61.0 (-13.9)**	**114.3 (+5.3)**	**157.5 (+74.4)**	**139.7 (+61.7)**	**510.5 (+111.4)**
Brookings 2017	**40.6 (-13.5)**	**88.9 (+14.0)**	**5.1 (- 103.9)**	**160.0 (+76.9)**	**157.5 (+79.5)**	**452.1 (+53.0)**
Pierre 2016	**99.6 (+53.6)**	**30.5 (-49.5)**	**70.8 (-19.6)**	**65.6 (-37.2)**	**54.4 (+8.4)**	**320.9 (-7.5)**
Pierre 2017	**48.3 (+2.3)**	**34.0 (-46.0)**	**79.8 (-10.6)**	**1.5 (-64.5)**	**95.8 (+48.9)**	**259.3 (-69.1)**
Ideal 2017	**53.3 (-15.8)**	**77 (-19.0)**	**6.4 (-92.7)**	**6.4 (-68.5)**	**201.4 (+144.5)**	**344.4 (-51.6)**

Table 1.3. Monthly temperature data collected throughout the growing period (GP) for all environments (2016 and 2017) in South Dakota (numbers in parentheses indicate differences from 1981-2010 average).

	April		*May*		*June*		*July*		*August*	
Temp. (ºC)	Max	Avg.	Max	Avg.	Max	Avg.	Max	Avg.	Max	Avg.
Brookings 2016	**13.8 (+1.0)**	**7.9 (+1.2)**	**20.8 (+1.4)**	**14.6 (+1.3)**	**27.3 (+2.3)**	**21.3 (+2.4)**	**27.1 (-0.7)**	**21.6 (+0.5)**	**26.3 (-0.4)**	**20.9 (+0.9)**
Brookings 2017	**13.3 (+0.5)**	**7.2 (+0.5)**	**19.4 (0)**	**13.3 (0)**	**26.1 (+1.1)**	**19.4 (+0.5)**	**28.9 (+1.1)**	**22.8 (+1.7)**	**23.3 (-3.4)**	**18.9 (-1.1)**
Pierre 2016	**15.8 (+0.2)**	**8.9 (+0.6)**	**22 (+0.9)**	**14.4 (0)**	**30.1 (+4.4)**	**22.2 (+2.2)**	**32.3 (+0.6)**	**24.4 (+0.5)**	**30.2 (+0.4)**	**22.7 (+0.6)**
Pierre 2017	**16.2 (+0.6)**	**8.9 (+0.5)**	**22.2 (+1.1)**	**15.1 (+0.7)**	**29.1 (+2.4)**	**21.6 (+1.6)**	**34.2 (+2.5)**	**26.1 (+2.2)**	**27.3 (+3.3)**	**20.2 (+3.1)**
Ideal 2017	**16.7 (+1.4)**	**10.0 (+1.3)**	**22.2 (+1.1)**	**15.0 (+0.5)**	**30.6 (+3.9)**	**22.2 (+2.1)**	**36.7 (+5.5)**	**27.8 (+3.6)**	**27.8 (-2.8)**	**21.1 (-2.5)**

Table 1.4. Total days with temperatures above 25 and 30 °C and total precipitation during critical growth stages for seeding rate experiments conducted at Brookings, SD in 2016 and 2017.

	Month	Days	Days > 25 ºC	Days > 30 ºC	Precipitation (mm)
	June	1-10	4	2	17.8
	June	11-20	10	4	96.5
2016	June	21-30	8	0	0.0
	July	1-10	5	1	91.4
	July	11-20	8	2	40.6
	July	21-31	10	3	25.4
					Total = 271.8
	June	1-10	10	5	0.0
	June	11-20	6	1	5.1
2017	June	21-30	3	0	0.0
	July	1-10	10	4	0.0
	July	11-20	9	4	88.9
	July	21-31	10	2	71.1
					Total = 165.1

Table 1.5. Total days with temperatures above 25 and 30 °C and total precipitation during critical growth stages for seeding rate experiments conducted at Pierre, SD in 2016 and 2017.

	Month	Days	Days > 25 ºC	Days > 30 ºC	Precipitation (mm)
	June	1-10	8	3	16.0
	June	11-20	9	5	31.0
2016	June	21-30	10	5	23.9
	July	1-10	9	6	22.9
	July	11-20	10	8	5.3
	July	21-31	11	8	0.3
					Total = 99.3
	June	1-10	10	9	0.5
	June	11-20	9	2	52.3
2017	June	21-30	5	3	26.9
	July	1-10	10	10	0.5
	July	11-20	10	10	0.5
	July	21-31	11	11	0.5
					Total = 81.3

Table 1.6. Total days with temperatures above 25 and 30 °C and total precipitation during critical growth stages for seeding rate experiments conducted at Ideal, SD in 2017.

Month	**Days**	**Days > 25 ºC**	**Days > 30 ºC**	**Precipitation (mm)**
June	1-10	9	8	0.8
June	11-20	9	8	4.8
June	21-30	9	4	0.8
July	1-10	10	10	0.0
July	11-20	10	10	3.3
July	21-31	11	11	3.1
				Total = 12.8

Table 1.7. Seeding rate and variety effects on plant stand, plant height, lodging severity, days to flowering, days to maturity, pod shatter, seed yield, oil concentration and oil yield in *B. carinata* grown at Brookings in 2016.

Brookings 2016											
Seeding Rate ($kg\ ha^{-1}$)	**Plants (m^{-2})**	**Plant Height (cm)**	**Lodging Severity[1]**	**Shatter (%)**	**Flower Days**	**Maturity Days**	**Pods $Plant^{-1}$**	**Seeds Pod^{-1}**	**Seed Yield ($kg\ ha^{-1}$)**	**Oil Con. ($g\ kg^{-1}$)**	**Oil Yield ($kg\ ha^{-1}$)**
4.5	**79 (c)***	**119 (a)**	**4.6 (b)**	**13.1 (a)**	**54**	**92 (d)**	**82 (a)**	**15**	**1248 (b)**	**357**	**446 (ab)**
9	**95 (c)**	**117 (a)**	**7.1 (ab)**	**10.0 (b)**	**54**	**93 (c)**	**70 (ab)**	**15**	**1348 (ab)**	**338**	**457 (ab)**
13.5	**142 (b)**	**110 (b)**	**7.5 (ab)**	**10.0 (b)**	**54**	**94 (b)**	**55 (bc)**	**15**	**1492 (a)**	**344**	**517 (a)**
18	**179 (a)**	**102 (b)**	**8.6 (a)**	**5.0 (c)**	**54**	**95 (a)**	**48 (c)**	**15**	**1156 (b)**	**334**	**385 (b)**
Mean	**124**	**113**	**7**	**9.5**	**54**	**94**	**64**	**15**	**1311**	**344**	**451**
Variety											
A110	**124**	**114**	**6.9**	**10.0**	**54**	**95**	**65**	**15**	**1188 (b)**	**351**	**423**
A120	**123**	**113**	**7.1**	**9.1**	**54**	**93**	**63**	**15**	**1422 (a)**	**336**	**479**
Mean	**124**	**113**	**7**	**9.5**	**54**	**94**	**64**	**15**	**1311**	**344**	**451**

*Within each column, means followed by the same letter are not significantly different ($P \leq 0.05$).

[1] 1= erect, 9=completely lodged

Table. 1.8. Seeding rate and variety effects on plant stand, plant height, lodging severity, days to flowering, days to maturity, pod shatter, seed yield, oil concentration and oil yield in *B. carinata* grown at Brookings in 2017.

Brookings 2017											
Seeding Rate ($kg\ ha^{-1}$)	**Plants (m^{-2})**	**Plant Height (cm)**	**Lodging Severity[1]**	**Shatter (%)**	**Flower Days**	**Maturity Days**	**Pods $Plant^{-1}$**	**Seeds Pod^{-1}**	**Seed Yield ($kg\ ha^{-1}$)**	**Oil Con. ($g\ kg^{-1}$)**	**Oil Yield ($kg\ ha^{-1}$)**
4.5	**37 (d)***	**111 (a)**	**2.0 (c)**	**6.9 (a)**	**59 (b)**	**94 (c)**	**106**	**16**	**1107 (ab)**	**397**	**439**
9	**60 (c)**	**109 (b)**	**2.9 (b)**	**6.9 (a)**	**60 (b)**	**96 (b)**	**101**	**16**	**1140 (a)**	**373**	**423**
13.5	**75 (b)**	**105 (c)**	**3.6 (b)**	**5.6 (ab)**	**60 (b)**	**97 (b)**	**97**	**16**	**1027 (b)**	**393**	**406**
18	**96 (a)**	**100 (d)**	**4.8 (a)**	**3.8 (b)**	**63 (a)**	**99 (a)**	**90**	**16**	**1019 (b)**	**397**	**405**
Mean	**67**	**106**	**3.3**	**5.8**	**61**	**97**	**98**	**16**	**1073**	**390**	**418**
Variety											
A120	**61 (b)**	**107**	**3.3**	**5.9**	**61**	**97**	**92**	**16**	**1108**	**417 (a)**	**402**
M01	**73 (a)**	**106**	**3.3**	**5.6**	**61**	**96**	**104**	**15**	**1038**	**363 (b)**	**434**
Mean	**67**	**107**	**3.3**	**5.8**	**61**	**97**	**108**	**16**	**1073**	**390**	**418**

*Within each column, means followed by the same letter are not significantly different ($P \leq 0.05$).

[1] 1= erect, 9=completely lodged

Table 1.9. Seeding rate and variety effects on plant stand, plant height, lodging severity, days to flowering, days to maturity, pod shatter, seed yield, oil concentration and oil yield in *B. carinata* grown at Pierre in 2016.

Pierre 2016

Seeding Rate (kg ha^{-1})	Plants (m^{-2})	Plant Height (cm)	Lodging Severity[1]	Shatter (%)	Pods Plant $^{-1}$	Seeds Pod^{-1}	Seed Yield (kg ha^{-1})	Oil Con. (g kg^{-1})	Oil Yield (kg ha^{-1})
4.5	36 (b)*	110 (a)	1.0 (c)	16.9 (a)	83 (a)	17	650 (b)	323 (b)	189 (b)
9	58 (a)	109 (a)	1.0 (c)	11.9 (b)	74 (a)	17	734 (a)	326 (ab)	251 (a)
13.5	57 (a)	104(b)	2.4 (b)	9.4 (bc)	56 (b)	17	741 (a)	332 (a)	233 (a)
18	72 (a)	99 (c)	2.8 (a)	6.9 (c)	38 (c)	17	662 (b)	326 (a)	239 (a)
Mean	56	105	1.8	11.3	63	17	697	327	228
Variety									
A110	59	105	1.8	12.8 (a)	64	17	667	327	218
A120	53	105	1.8	9.7 (b)	62	17	727	327	238
Mean	56	105	1.8	11.3	63	17	697	327	228

*Within each column, means followed by the same letter are not significantly different (P≤0.05).

[1] 1= erect, 9=completely lodged

Table 1.10. Seeding rate and variety effects on plant stand, plant height, lodging severity, days to flowering, days to maturity, pod shatter, seed yield, oil concentration and oil yield in *B. carinata* grown at Pierre in 2017.

			Pierre 2017			
Seeding Rate (kg ha^{-1})	**Plants (m^{2})$^{-1}$**	**Plant Height (cm)**	**Lodging Severity[1]**	**Shatter (%)**	**Pods Plant $^{-1}$**	**Seeds Pod^{-1}**
4.5	**15 (b)***	**71 (a)**	**1.6 (b)**	**21.3 (a)**	**190**	**12**
9	**19 (b)**	**69 (a)**	**1.4 (b)**	**21.3 (a)**	**182**	**11**
13.5	**30 (ab)**	**65 (b)**	**2.0 (ab)**	**18.1 (a)**	**180**	**11**
18	**45 (a)**	**64 (b)**	**2.5 (a)**	**10.6 (b)**	**130**	**10**
Mean	**28**	**68**	**1.9**	**17.9**	**170**	**11**
Variety						
A120	**27**	**68**	**1.8**	**18.8**	**202**	**11**
M01	**28**	**67**	**1.9**	**16.9**	**140**	**11**
Mean	**28**	**68**	**1.9**	**17.9**	**170**	**11**

*Within each column, means followed by the same letter are not significantly different (P≤0.05).

[1] 1= erect, 9=completely lodged

Table 1.11. Seeding rate and variety effects on plant stand, plant height, lodging severity, days to flowering, days to maturity, pod shatter, seed yield, oil concentration and oil yield in *B. carinata* grown at Ideal in 2017.

Ideal 2017									
Seeding Rate (kg ha^{-1})	**Plants (m^{-2})**	**Plant Height (cm)**	**Lodging Severity[1]**	**Shatter (%)**	**Pods Plant^{-1}**	**Seeds Pod^{-1}**	**Seed Yield (kg ha^{-1})**	**Oil Con. (g kg^{-1})**	**Oil Yield (kg ha^{-1})**
4.5	**22 (c)***	**75 (a)**	**1.5 (c)**	**8.1**	**108 (a)**	**15**	**252 (b)**	**291 (c)**	**73 (b)**
9	**33 (b)**	**68 (bc)**	**2.3 (b)**	**5.6**	**77 (b)**	**14**	**343 (ab)**	**316 (b)**	**109 (ab)**
13.5	**48 (a)**	**72 (ab)**	**2.9 (a)**	**5.6**	**52 (c)**	**14**	**408 (a)**	**303 (bc)**	**124 (a)**
18	**48 (a)**	**67 (c)**	**3 (a)**	**5.6**	**48 (c)**	**14**	**348 (ab)**	**334 (a)**	**116 (a)**
Mean	**38**	**70.4**	**2.4**	**6.3**	**71**	**14**	**338**	**311**	**106**
Variety									
A120	**38**	**74 (a)**	**2.4**	**6.6**	**79 (a)**	**15 (a)**	**340**	**312**	**106**
M01	**37**	**67 (b)**	**2.4**	**5.9**	**64 (b)**	**13 (b)**	**336**	**311**	**105**
Mean	**38**	**70**	**2.4**	**6.3**	**71**	**14**	**338**	**312**	**106**

*Within each column, means followed by the same letter are not significantly different (P≤0.05).

[1] 1= erect, 9=completely lodged

Figure 1.1. Stand establishment for the 9 kg ha^{-1} seeding rate at Pierre (left) and Brookings (right) in 2017.

Figure 1.2. Stand establishment for the 13.5 kg ha^{-1} seeding rate at Pierre (left) and Brookings (right) in 2017.

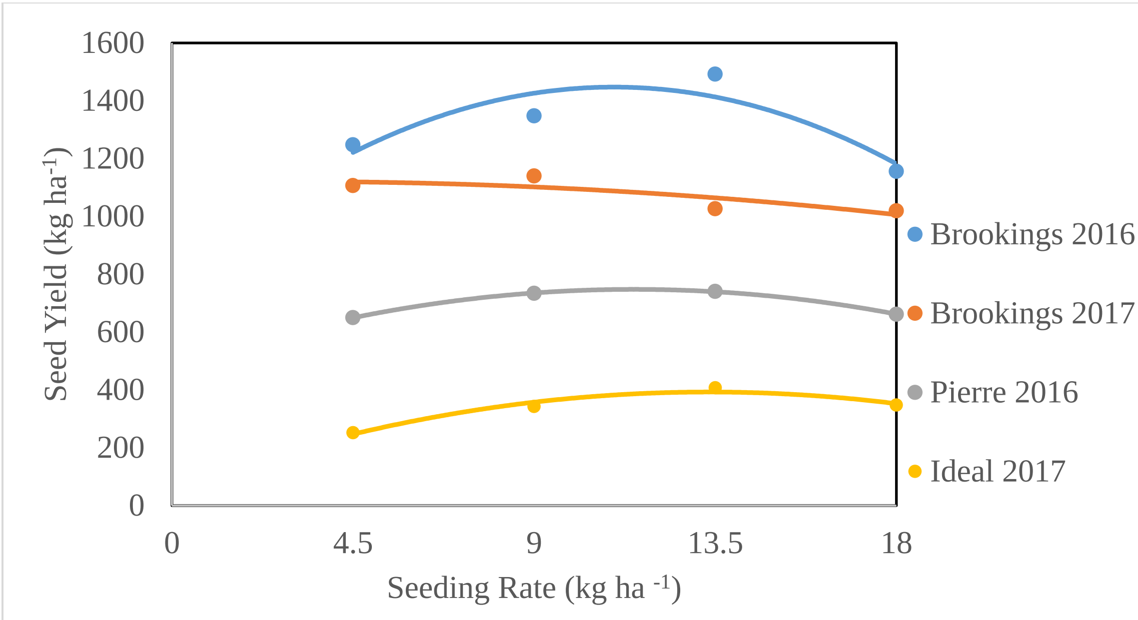

Figure 1.3. Seed yield response of *B. carinata* to seeding rate (4.5, 9, 13.5, and 18 kg ha^{-1}) grown in five environments in South Dakota: Brookings (2016 and 2017) Pierre (2016), and Ideal (2017). Means are averaged over two varieties.

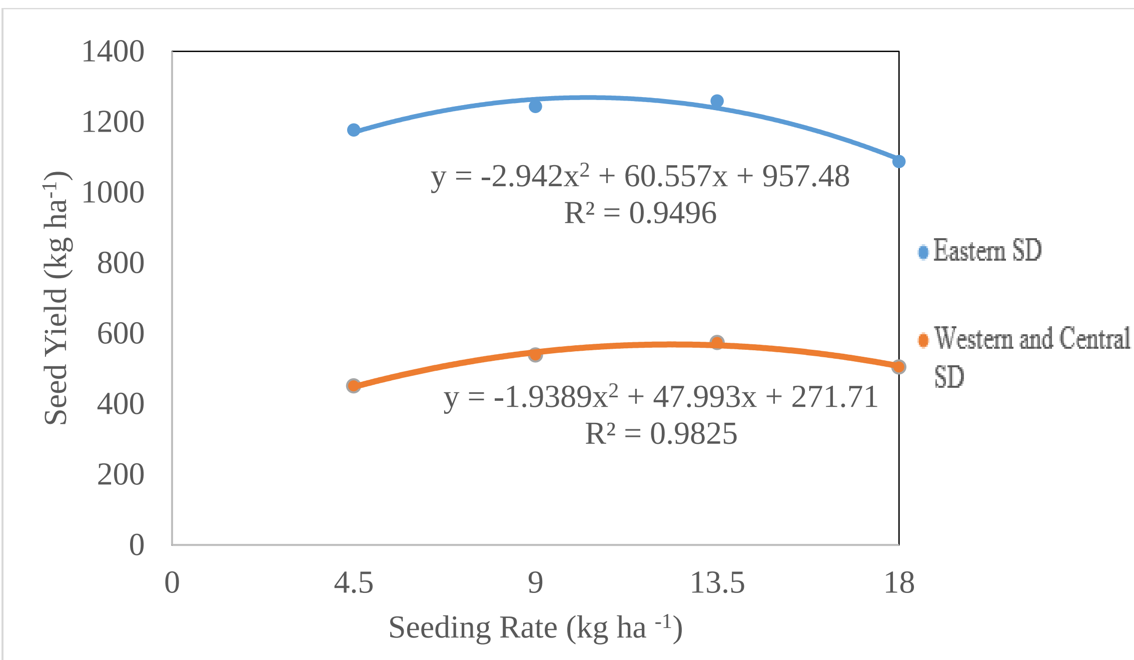

Figure 1.4. Seed yield response of *B. carinata* to seeding rate (4.5, 9, 13.5, and 18 kg ha^{-1}) grown in two regions in South Dakota: Eastern (Brookings) and Central and Western (Pierre and Ideal) in 2016 and 2017. Means are averaged over years and varieties.

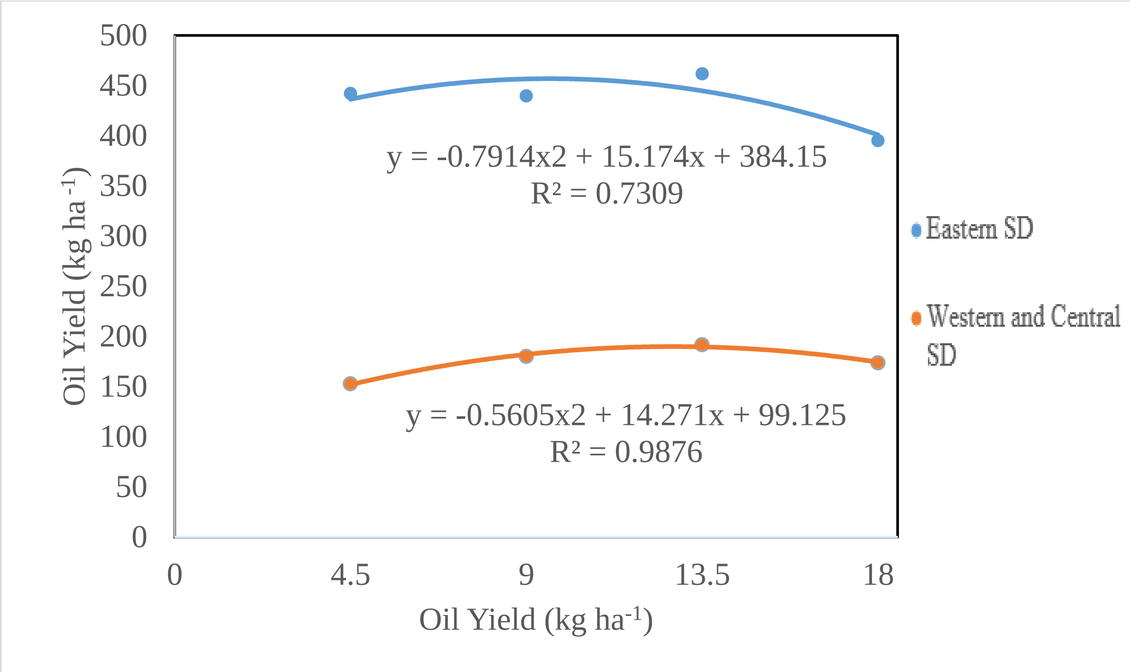

Figure 1.5. Seed oil yield response of *B. carinata* to seeding rate grown in two regions in South Dakota: Eastern (Brookings) and Central and Western (Pierre and Ideal) in 2016 and 2017. Means are averaged over years and varieties.

CHAPTER 2:
ETHIOPIAN MUSTARD (*BRASSICA CARINATA*) RESPONSE TO NITROGEN FERTILIZER RATES AT TWO LOCATIONS IN SOUTH DAKOTA

LITERATURE REVIEW

B. carinata is a new crop to the NGP region, therefore there is a lack of information regarding optimal nitrogen rates to be used in South Dakota. This is important considering that cost of fertilizer is the greatest expense in crop production followed by seed costs (Zentner et al., 2012). More specifically, nitrogen is the greatest energy input in the production of oilseeds (Gan et al., 2007; Zentner et al., 2012). Using the appropriate nitrogen rate is very important to achieve high yields while minimizing production costs and reducing environmental impacts (Gan et al., 2007). Research in *Brassica* species has shown that requirements for nitrogen (N), phosphorous (P), and potassium (K) are like those of small grains, while sulfur (S) requirements are greater than in most crops (Franzen, 2013; Jones et al., 2016; Canola Watch, 2012). *Brassica* species are small seeded crops which tend to react to environmental conditions much more variably than small grains and are known to be extremely sensitive to seed-placed fertilizer salts. Nitrogen rate is believed to influence many factors in *B. carinata* production including: days to flowering, days to maturity, lodging, pod shatter, number of pods plant^{-1}, number of seeds pod^{-1}, seed weight, seed oil concentration, seed yield, and seed oil yield. Due to its close relation to the more common *Brassica* species used in canola production, literature regarding *B. rapa, B.napus, and B. juncea* will be used as reference where *B. carinata* information is lacking.

Brassica species have an indeterminate growth habit which means that the plants continue to grow and branch utilizing nutrients, space, water, and light even after flowering has been initiated (Koening et al., 2011). While adequate branching is very important to attain yield goals, a combination of indeterminate growth habit and excessive N fertilization rates can present management problems. In *B. napus* plant height, number of sub-branches, and number of pods plant^{-1} were shown to increase in response to N fertilizer rates; however, the number of seeds pod^{-1} has not been shown to be influenced by N fertilizer rates (Karamzadeh et al., 2010; Marquard and Gendy, 1989). Increases in plant height and sub-branch formations coupled with increases in pod number are believed to be responsible for the increases in lodging at greater N rates.

When N is applied at high rates (>100 kg ha^{-1}), increases in lodging may correspond to reductions in yield potential (Wright et al., 1988). High N rates prolong the vegetative growth stage of the plants resulting in taller, top-heavy plants and increases susceptibility to lodging (Pan et al., 2012). Lodging can have severe impacts on yield and seed quality due to the prevention of vital nutrients relocating into the seed (Grant and Bailey 1993). Additionally, increases in lodging can trap unwanted moisture which provides a habitable microclimate for sclerotinia (*Sclerotinia sclerotiorum*) infections to develop; sclerotinia infections can have severe negative consequences on seed and oil yields (Hanson, 2008). This is of extreme importance because all *Brassica* species are susceptible to sclerotinia stem rot (Hanson, 2008). Lastly, severe lodging can impede on successful harvesting due to uneven plant heights and non-uniform maturation rates in the field. (McKenzie, 2011).

In some cases, increasing nitrogen fertilizer rates has resulted in reduced days to flowering while increasing the flowering period in *Brassica* species; this effect depends on the species being assessed (Gan et al., 2007). Reduction in number of days to flowering can be beneficial to avoid the high temperatures during flowering and seed filling period (June-July) which are common in the semi-arid regions of the NGP; high temperatures during the critical growth stages can result in decreased yields. Increasing applied N may prolong life of leaves thus delaying maturity (or increasing number of days to maturity) (Wright et al. 1988; Jackson 2000). This can be detrimental in areas with shorter growing seasons because harvest can be delayed, increasing risks to yield losses due to fall frost in late-maturing varieties (Grant and Bailey, 1993; Canada Canola Council, 2016; Kutcher et al., 2000). In addition, delayed maturity may result in increases in green seed (immature seed) production. Green seed has high levels of chlorophyll, hence the name, and these higher levels of chlorophyll decrease seed quality and make processing more difficult, reducing profitability to producers. (CCC, 2016).

In *B. napus*, 1000 seed weight was shown to increase in response to increase in N fertilizer rates (Karamzadeh et al., 2010). Seed weight is a very important aspect of seed quality and can influence profitability depending on whether the seed will be used for industrial applications or for biofuel production. Increases in N fertilizer rates have been shown to decrease oil concentration in *Brassica napus* (Karamzadeh et al., 2010; Jackson, 2000; Taylor et al., 1991). Environmental factors such as temperature and moisture also influence oil concentration in *Brassica* species. Periods of high temperatures and low soil moisture during the flowering and seed-filling periods in canola have been shown to reduce oil concentrations (Morrison and Stewart, 2002; Pritchard et al., 2000). Conversely, cool and wet conditions have been shown to prolong seed maturation which results in greater oil accumulation (Pritchard et al., 2000). High temperatures accelerate growth stages which result in reduced seed filling periods (Faraji

2012; Zanetti et al., 2009). Oil concentration is often the most important factor in *Brassica* species production, with higher oil content of seeds resulting in higher seed quality and increasing profitability for the producers.

In the U.S., canola quality standards for oil concentration are often ~40%, with penalties for each percent below that standard (Pritchard et al., 2000) thus, environmental conditions must be considered when determining production goals to maximize profits. Despite the negative correlation between seed oil concentration and applied nitrogen, total seed oil yield can still increase with increase in N fertilizer rate to a certain point (~100 kg ha^{-1} N) at which point total oil yield increase begins to taper off (Karamzadeh et al., 2010 and Jackson, 2000; Harker et al., 2012). In *B. carinata*, seed oil concentration and seed protein concentration are inversely proportional, which can provide useful information regarding fertilization regimes to maximize seed oil or seed protein yields based on the designated end use of the seed (Pan et al., 2012). For example, rapeseed protein has many industrial applications, so increasing fertilizer rates to increase protein concentration and subsequent overall protein yield may be beneficial to increase profitability in areas in which oil production may be limited due to environmental factors. On the other hand, elevated temperatures and low precipitation, particularly during the critical periods of flowering and seed-fill (June-July), is detrimental to oil production (Gan et al., 2007). For this reason, weather is very important aspect of seed quality and can influence profitability depending on whether the seed will be used for industrial applications or biofuel production. Increases in N fertilizer rates have been shown to decrease oil concentration in *Brassica napus* (Karamzadeh et al., 2010; Jackson, 2000; Taylor et al., 1991).

Seed yield is a function of the effects and interactions of many environmental (precipitation, temperature) and soil factors (texture, N fertility, and organic matter content). In oilseed production, residual soil N plays a key role in determining appropriate N application rates. Residual soil N and pre-plant N applications are responsible for early season vegetative growth and development, so pre-plant soil testing is important (Wright et al., 1998). In addition, it is believed that the improved nutrient cycling and water holding capacity of soils with high organic matter enhance yields (Harker et al., 2012). Overall seed yield in *Brassica* species, not portioned into individual components such as protein or oil, increases in response to N fertilizer rate. In research conducted in Canada, all *Brassica* species, including *B. carinata,* begin to reach maximum yield potential at ~100 kg ha^{-1} N, with some variation among species though these yields were not significantly different than seed yields at ~75 kg ha^{-1} N (Gan et al., 2007; Johnson et al., 2013; Pan.et al., 2012). Seed yield response to increasing N rate decreases as N rate increases beyond 100 kg ha^{-1} and this was attributed to decreasing nitrogen use efficiency (NUE) and is true across many *Brassica* species (Hocking et al., 2002, Gan et al., 2007). These N fertilizer limits served as a guideline for this study to minimize unnecessary over-application.

As mentioned earlier, there is an inverse relationship between seed oil concentration and N fertilization rate hence production goals must be factored into N fertilizer application decisions. This is of importance when making the most economic fertilization decisions based on production goals, whether it is for maximizing seed oil or seed protein yield. Due to the variability in total seed yield resulting from nitrogen fertilization, an analysis must be performed to determine the Economic Optimum N Rate

(EONR) based on the producers desired goals. South Dakota has extremely diverse climates ranging from humid temperate (East River) to semi-arid (Central SD and West River) for which the Missouri River acts as the dividing line. Environmental conditions have huge implications for crop production systems, yield potentials and fertilizer inputs (Franzen, 2013). The differences between East and West River is stark, with East River more suited for corn and soybean production, while West River is primarily ranching and dry-land farming. In Brassica species, high temperatures and drought stress conditions during flowering may result in flower abortion or seed development failure (Morrison and Stewart, 2002; Gan et al., 2007). Such conditions are common in the semi-arid regions of South Dakota and have raised concerns over the efficacy of canola production in these environments.

Previous research done in North Dakota (ND), which has very similar climatic conditions as South Dakota, has shown that increases in soil organic matter have resulted in significantly greater yield potentials in canola production. This research recommends that canola growers in cooler and wetter areas of eastern North Dakota should not apply more than 168 kg ha^{-1} N while growers in the warmer and drier western areas of the state should not apply more than 135 kg ha^{-1} N without risking drastic profit loss. These N rates are meant to represent caps for seed yield potential and should not be optimal rates (Franzen, 2013). These differences in N requirements are due to fact that high temperatures and limited rainfall, in Western ND and SD can have severe impacts on seed yield and oil content of *Brassica* species. Additional research done in the NGP have illustrated the potential use of canola as a low-input crop with the added benefit of diversifying cropping systems (Potts et al., 2003). While concerns regarding canola production in these regions are valid, research has shown that *B. carinata* is better suited to semi-arid environments and low-input cropping systems compared to other *Brassica* species (Cardone et al., 2002). The objectives of this research were to i) evaluate the response, in seed yield and other agronomic traits, of two *B. carinata* varieties to five different fertilizer rates, ii) determine if variety x N rate interactions occurred, and iii) determine the N rate for economic optimum yield at two locations in South Dakota.

MATERIALS AND METHODS

The study was conducted at two locations, near Brookings (44.309435ºN, -96.671718ºW) and Pierre (44.292860ºN, -100.006049ºW) in South Dakota in 2015 and 2016. The experimental design was a randomized complete block design (RCBD) with treatments replicated four times. Treatments included five different N fertilizer rates: 0, 28, 56, 84, and 140 kg ha^{-1}, and two *B. carinata* cv. (‘A110’ and ‘A120’) arranged in a factorial design to give a total of ten treatments within each replication, for a total of 40 plots per location per year. In 2015, plots were planted on April 3 at Brookings and April 16 at Pierre. In 2016 the plantings dates were April 26 at Brookings and April 14 at Pierre. Planting was accomplished using a seven-row Hege 500® (Wintersteiger-Austria) at Brookings; seeding at Pierre and Ideal was done using a Light Duty Grain Drill® (Almaco- Iowa). For the Brookings location, individual plot size was 1.62 x 9.14 meters (14.86 m^2) and 1.62 x 8.23 meters (13.37 m^2) at Pierre. Each plot had seven rows, 22 cm apart. The seeding rate was 11 kg ha^{-1} at both locations.

The Brookings location (conventional tillage), located within Aurora Agricultural Experimental Station approximately 8 miles east of Brookings, has a slightly acidic (pH~5.7), and medium-textured soil (Table 2.1). The previous crop in both years was winter wheat (WW). The Pierre location (no-till), located within the Dakota Lakes Research Farm, also has a slightly acidic (pH~6.1), medium-textured soil; the previous crops were teff (*Eragrotis tef*) in 2015 and corn (*Zea mays*) in 2016 (Table 2.1). Soil analysis details for each location in each year are shown on Table 2.1. Nitrogen fertilizer in the form of urea (46% N) was broadcast manually using an automatic hand-held spreader to ensure even application soon after planting.

Weeds were managed with pre-plant application at all locations of Prowl H_20 (Pendimethalin, BASF, Research Triangle, NC) herbicide. The herbicide was applied at a rate of 2.8 L ha^{-1} and incorporated 2 inches deep via two-pass incorporation. Herbicide application was at approximately two weeks before planting for all locations and years. Once the crop had emerged, weeds were managed by manually removing weeds from within each plot as necessary.

Four weeks after seeding, plant stand establishment (%) was assessed to determine crop emergence; percent stand establishment was used along with seeding population and germination rates to estimate plants/m^2. Days to flowering (50% of flowers open within each plot) and days to maturity (50% of plant with pods mature within each plot) were also determined for each plot. At physiological maturity, average plant height was determined by measuring height of five random plants within each plot from soil line to the top of the plant. Shattering notes were taken based on percent of pods shattered at the time of harvest. In 2016, whole plant samples were obtained from all plots and both locations (n=80), and the number of seeds per 15 pods were determined; from these values, the average number of seeds pod^{-1} were determined.

Once *B. carinata* had appropriately dried down, it was harvested using a Kincaid 8XP® crop research combine (Kincaid Equipment and Manufacturing- Haven, KS) with the assistance of the H2 High Capacity GrainGage® (Juniper Systems Inc.- Logan, UT). Once the plots were harvested, the seed was cleaned and sieved and total seed yield (kg) and bulk density were determined. Bulk density of the samples was used in place of 1000 seed weight as a measurement of seed density and quality; bulk density was measured in terms of grams per .47 L (g .47L^{-1}). Sub-samples of the harvested seed were collected and placed into individual manila envelopes and stored in a cold room (~10º C) for oil content determination. Two replications for all nitrogen fertilizer treatments were sent to SGS Mid-West Seed Services, Inc. (Brookings, SD, USA) for oil content analysis using a hexane solvent extraction. The results of this analysis were used to calibrate the "minispec mq" (Bruker- Billerica, Massachusetts) NMR instrument for future *B. carinata* oil analysis. The remainder of the samples from both years and locations were then analyzed using the "minispec mq." Total oil yield (kg ha^{-1}) was determined by multiplying the total seed yield (kg ha^{-1}) by the oil concentration (%).

A combined analysis was conducted, including all data collected from two locations (Brookings and Pierre) over five N rates (0, 28, 56, 84, and 140 kg ha^{-1}) and two varieties ('A110' and 'A120') to determine whether the interactions between N rate, variety, and location influenced the agronomic traits evaluated. Fixed effects in the models were "N rate," "location," and "variety." The random effects in the model were "year" and "replication," which acted as a block. The agronomic traits were analyzed using analysis of variance (ANOVA) for a RCBD in RStudio (v0.99.903; https://www.rstudio.com/) using package "agricolae" (deMediburu, 2017). Fisher's Least

Significant Difference (LSD) was used to compare the differences among treatments at the 95% confidence level.

Yield data over years and locations were combined and used to perform an Economic Optimum N Rate (EONR) analysis. EONR is described as the N rate at which applying additional N results in a yield increase great enough to pay for the additional N applied; in short, EONR is the N rate that produces the greatest dollar return to N and is a valuable tool to maximize price margins for producers (Camberato and Nelsen, 2017). EONR, or a similar metric such as Maximum Return to Nitrogen (MRTN), is often used in other agronomic crops and can be calculated using the best-fit polynomial regression equation formed ($y=ax^2+bx+c$) when plotting seed yield (kg ha^{-1}) against N rate (kg ha^{-1}) (Figure 2.1). This is done to model the expected value (seed yield) against an independent variable (N rate). For the EONR analysis, prices of *B. carinata* (.411 \$ kg^{-1}) and current cost of N (\$.84 kg^{-1}) were used (Sitter, 2017); cost of N was calculated using urea (46%) as the source of nitrogen. EONR can then be calculated using the polynomial equation to solve the following formula:

Equation 2.1. Economic Optimum Nitrogen Rate (EONR).

$$EONR = \frac{\frac{\$/\,kg - N}{\$\text{ / kg - } \textit{B. carinata} \text{ seed}} - b}{2\ \times c}$$

Where:

\$/kg N= Cost of nitrogen fertilizer kg^{-1}

\$/kg seed= Selling price of *B. carinata* seed

b= Amount of increase or decrease (slope) in seed yield in response to N rate

c= Y-intercept, the expected yield when N rate is 0 kg ha^{-1}

RESULTS

Temperature and rainfall data were collected throughout the growing period for both years and locations (Table 2.2 and 2.3). The weather data was collected via weather stations managed by the South Dakota Agricultural Experiment Station located at each site. Mean temperatures throughout the growing season were similar to the 30- year average at Brookings in 2015. However, mean temperatures were 1.3^{o} C above average in the month of April. In 2015, Brookings received substantially lower rainfall totals in the months of April and June when compared to the 30-year average; however, above average rainfall totals in May and July brought the cumulative rainfall totals close to the long-term average. During the critical growth stages, temperatures often exceeded 25°C, but rarely exceeded 30°C; additionally, precipitation throughout this period occurred frequently, resulting in suitable growing conditions (Table 2.4). In 2016, the average temperatures throughout the growing season in Brookings were higher than the long-term average except for August. The month of June was warmer than the 30-year average by 2.4°C. In 2016, rainfall totals in the months of April, May, and June were close to the 30-year average; however, the months of July and August had nearly double the 30-year average totals for those months. The abundance of rainfall late in the growing season resulted in a greater cumulative rainfall totals than the 30-year average. Temperatures throughout the critical growth stages regularly exceeded 25°C, and surpassed 30°C often; total precipitation during this period was consistent (Table 2.4).

In 2015, the average temperatures at Pierre were close to the 30-year average throughout the growing season; however, the month of April had slightly higher temperatures while the month of May had slightly lower temperatures. In 2015, the month of April had substantially lower rainfall totals than the 30-year average; however, significantly greater rainfall totals in May and June resulted in a greater cumulative rainfall totals across the growing season. Temperatures similar to the long-term average coupled with regular precipitation events throughout the critical growth stages resulted in suitable growing conditions (Table 2.5). In 2016, average temperatures at Pierre were comparable to the 30-year average, except for June which was 2°C warmer. In 2016, Pierre exhibited drought conditions throughout the growing season. Specifically, during the critical growth stages, temperatures regularly exceed 30°C with limited total precipitation occurring during this period (Table 2.5).

Plant height was significantly influenced by nitrogen rate ($P \leq .001$), location ($P \leq .001$), and the location x variety interaction ($P \leq .003$) (Table 2.6). *B. carinata* plants were significantly taller in the 28, 56, 84, and 140 kg ha^{-1} N treatments (104, 107, 108, and 110 cm, respectively) compared to the control (98 cm). Optimal height was achieved at the 140 kg ha^{-1} N rate (110 cm) with these plants significantly taller than plants in the control or 28 kg ha^{-1}N treatment (Table 2.7). Across years, *B. carinata* plants were significantly taller at Pierre when compared to the Brookings location, with average plant heights of 109 and 102 cm, respectively. The variety "A120' was taller (106 cm) than 'A110' (104 cm) across locations, however the differences were not significant. The location x variety interaction was significant due to the fact that there was no significant difference in plant height at the Pierre location (110 for A110 vs 108 for A120); while at Brookings, 'A120' was significantly taller than 'A110,' (104 vs 100) cm, respectively.

Lodging severity was significantly influenced by location ($P<.001$), but was not influenced by the other factors or their interactions (Table 2.6). Lodging tended to increase with increasing nitrogen fertilizer rate, with the greatest lodging occurring at the 140 kg ha^{-1} N rate; conversely, lodging was least severe in the 0 and 56 kg ha^{-1} nitrogen rate (Table 2.7). Lodging severity score was significantly higher at Pierre than at Brookings, with average lodging severity values being 3.4 and 1.8, respectively (Table 2.8).

Number of days to maturity was significantly influenced by nitrogen rate ($P \leq .001$) and location ($P \leq .001$) only, with no other factors or their interactions being significant (Table 2.6). Number of days to maturity significantly increased in response to N rate; N rate of 140 kg ha^{-1} resulted in the most days to maturity while the plants in the control treatment took the shortest amount of time to reach maturity with values of ~113 and ~110 days, respectively. (Table 2.7). Days to maturity was not significantly influenced by location, despite plants at Brookings maturing one day earlier than plants at Pierre (Table 2.8). Days to maturity was not influenced by variety, with both "A110' and "A120' maturing in ~112 days (Table 2.8).

Pod shatter was significantly influenced by location ($P \leq .001$) and variety ($P = .017$); no other factors or their interactions were significant (Table 2.6). While not significant, pod shatter (%) decreased with increasing nitrogen rates with shatter greatest in the control treatment (3.9%) and lowest in the 140 kg ha^{-1} (2.6%) (Table 2.7). Percent shatter of the pods was significantly influenced by location with shatter occurring more extensively at Pierre than at Brookings (Table 2.8). Pod shatter was not significantly influenced by variety; however, 'A110' exhibited greater pod shatter than 'A120' with values of 4.0 and 2.4%, respectively (Table 2.8).

Seed yield was significantly influenced by nitrogen rate (P≤.001), location (P≤.001), and variety (P=.045); however, interactions were not statistically significant (Table 2.6). Total seed yield increased in response to N rate, with greatest seed yields occurring in the 84 kg ha^{-1} N rate (1744 kg ha^{-1}); however, this value was not statistically different from the yield obtained at N rates of 56 or 140 kg ha^{-1}. The lowest seed yields, 1320 kg ha^{-1}, were obtained in the control treatment (Table 2.7). Seed yield was plotted against N rate and fitted using a polynomial equation ($y = -0.0352x^2 + 7.7171x + 1328.6$) and a R^2 value (.979), confirming optimal yields at the 84 kg ha^{-1} N treatment (Figure 2.1). Average seed yields were significantly greater at the Brookings location compared to Pierre with values of 1690 and 1486 kg ha^{-1}, respectively (Table 2.8). While the ANOVA results indicate a significant difference among varieties in terms of total seed yield, no significant differences were seen when performing pairwise comparisons; however, 'A120' did have better performance than 'A110' with total seed yields being 1630 and 1546, respectively (Table 2.8).

Seed oil concentration was significantly influenced by N rate (P≤.001) and location (P≤.001) (Table 2.6). Seed oil concentration decreased linearly in response to increasing N rate. Seed oil concentration was plotted against N rate and can be explained by the following linear equation: $y= -0.2868x + 337.91$ (R^2=.947) (Figure 2.2). The greatest oil concentration (338 g kg^{-1}) was seen in the control treatment while the lowest oil concentration (299 g kg^{-1}) was seen in the 140 kg ha^{-1} N rate (Table 2.7). In addition, location had a significant impact on oil concentration as the seed from the Brookings location had greater oil concentrations (347 g kg^{-1}) than at Pierre (294 g kg^{-1}). Oil concentration was not significantly influenced by variety, with seed of ‘A110’ and ‘A120’ having oil concentrations of 321.3 and 319.1 g kg^{-1}, respectively (Table 2.8).

Total oil yield was significantly influenced by N rate ($P \leq .001$) and location ($P \leq .001$) (Table 2.6); total oil yield increased in response to N rate before leveling off at ~84 kg ha^{-1} in a curvilinear manner. The lowest oil yields (484 g kg^{-1}) were observed in the control while the greatest oil yields (542 g kg^{-1}) were seen in the 84 kg ha^{-1} N rate. At N rates greater than 84 kg ha^{-1}, there appears to be a leveling off, at which oil yields begin to decrease. Total oil yield was plotted against N rate and can be explained by the following equation: $y = -0.012x^2 + 2.1803x + 443.29$ (R^2=.9627) (Table 2.7 and Figure 2.3). Oil yield was significantly influenced by location, as the Brookings location produced greater average oil yields than the Pierre location, with values of 582 and 427 kg ha^{-1}, respectively. Total oil yield was not significantly influenced by variety (Table 2.8).

In 2016, the number of seeds pod^{-1} was influenced by N rate ($P \leq .001$), variety (P=.036), and the nitrogen rate x location interaction (P=.002) was significant; no other factors or their interactions were statistically significant (Table 2.9). At Pierre optimal number of seeds pod^{-1} occurring in the 28 kg ha^{-1} N rate, (17 seeds) and the least amount of seeds pod^{-1} occurring in the control treatment, (14 seeds) with the number of seeds pod^{-1} not significantly different in the 28 and 56 kg ha^{-1} N rates. The number of seeds pod^{-1} was not significantly influenced by nitrogen rate at Brookings (Table 2.10).

The bulk density of the harvested seed was significantly influenced by nitrogen rate (P=.016) and variety ($P \leq .001$), but none of the other factors or their interactions were significant (Table 2.9). Bulk density increased in response to nitrogen rate, with the greatest bulk density occurring in the 56-140 kg ha^{-1} treatments, although they were not significantly different from each other. The optimal bulk density occurred in the 56 kg ha^{-1} treatment while the lowest bulk density was found in the control with values of 353 and 338 g .47 L^{-1}, respectively (Table 2.10). Location did not significantly influence bulk density; however, bulk density was greater at Pierre than at Brookings by ~3 g .47 L^{-1} (Table 2.10). Bulk density was significantly influenced by variety, with 'A120' producing a denser seed by ~14 g .47L^{-1} (Table 2.11).

DISCUSSION

The objectives of this research were to i) evaluate the response, in seed yield and other agronomic traits, of two *B. carinata* varieties to five different fertilizer rates, ii) determine if variety x N rate interactions occurred, and iii) determine the N rate for economic optimum yield at two locations in South Dakota. The stark contrasts among environments and tillage systems (conventional vs no-till) provided an opportunity to determine the optimum nitrogen rate for each location and tillage system. Any significant differences among agronomic traits across locations could thus be factored into a best management practice manual.

In this study, average plant density was ~85 plants/m^2 at Brookings and ~52 plants/m^2 at Pierre. Plant populations at Brookings were within the recommended range (86-183 plants/m^2) for production in the NGP; however, the Pierre location values were well below the recommended rang (Agrisoma, 2015). This variation is likely due to differences in climatic conditions (temperature and precipitation) and management practices (no-till vs conventional tillage) which can have significant impacts on stand establishment and development (CCC 2016). High levels of variation were also seen within locations. At Brookings, soil compaction due to heavy equipment along with the occurrence of several clay-patches reduced stand development in some plots. At Pierre, variation in amount of corn residue among plots resulted in uneven emergence and stand development. In no-till systems, high residue can result in lower topsoil temperatures during the spring resulting in reduced germination and uniformity of plant development (Godsey et al., 2013). Also, high residue in no-till systems can inhibit the ability of the drill to cut through the residue and place the seed at the proper depth; when shallow seeding occurs, the roots will not be able to penetrate the soil surface which can result in seed drying (Godsey et al., 2013). The no-till grain drill used at Pierre may not have been heavy enough to properly cut through the high amounts of corn residue present, limiting planting depth; this may have resulted in reduced seed-soil contact and limited stand establishment. Use of larger, heavier planters in commercial production may help to mitigate this effect.

Plant establishment was not influenced by applied N rate due the fact that fertilizer was not applied until plant stands were already well established thus, all differences in plant establishment can be attributed to environmental and varietal factors. Despite the significantly lower stand establishment at Pierre, mustards in general, and *B. carinata* specifically, are known for their branching abilities which enable the crops to compensate for lower plant populations. Additional production of primary and secondary branches as well as increased pods plant^{-1} have a compensatory effect in *B. napus*, for example (Angadi et al., 2000 and Kirkland and Johnson, 2000). In agreement with previous studies done on canola, *B. carinata* plant height increased with increasing N rate and lodging severity was strongly associated with plant height (Pan et al., 2012; Wright et al. 1988). Although significant differences in plant height were seen across locations, the association between plant height and lodging severity in response to N rate remained intact. The influence of N rate on plant height and lodging should be taken into consideration in environments with potential lodging problems such as areas with high wind speeds and high rainfall. Such environments may require reductions in N fertilizer to reduce potential yield losses.

Days to maturity increased with increasing N rate, which confirms findings from previous studies; these findings suggest that increased nitrogen rates can result in delayed crop maturity, due to prolonged periods of vegetative growth (Brown et al., 2008; Wright et al. 1988; Jackson 2000). Delaying maturity may be beneficial to prolong the growing season to optimize yields in suitable environments. However, in the Northern Great Plains high temperature and drought stress often occur during flowering and seed-filling periods, the two most important growth stages determining yield potential. For this reason, delaying maturity may not be beneficial to the producer; instead, earlier planting dates and promoting earlier flowering to avoid these unfavorable conditions have been shown to increase yields in other brassica species (Kirkland Johnson, 2000). Importantly, even though differences in days to maturity among N treatments was significant, it was by no more than a few days suggesting that use of N rate to effectively influence maturity date may not be an effective or reliable tool; this is because many environmental factors also play a role (Gan et al., 2007).

Pod shatter (%) was not significantly influenced by N rate; however, as the N rate increased there was a decrease in pod shatter. These data suggest that increasing N rate can result in slight decreases in pod shatter likely explained by the influence that N fertilizer has on days to maturity. Increasing N rate may result in delayed maturity, thus decreasing the period where mature pods are exposed to hot and dry conditions which promote shattering. The Pierre location exhibited greater pod shattering than the Brookings location. The differences can most likely be explained by the stark differences in climates of these two locations. The Pierre location has higher temperatures, lower rainfall totals, and higher wind speeds than the Brookings location during the seed fill and dry-down periods. These prolonged hot and dry periods in combination with excessive wind speeds have been known to promote shattering (CCC 2016). ‘A110’ exhibited significantly greater pod shatter than “A120,’ which illustrates the importance of variety selection in oilseed production.

Seed yield increased in response to increasing N rate in a curvilinear manner, similar to previous reports in *B. juncea* (May et al., 2010). This curvilinear relationship is due to the decrease of nitrogen use efficiency (NUE) with increasing N rate reported in *B. juncea* (Gan et al., 2007; Hocking et al., 2012). Optimal yields were obtained in the 84 kg ha^{-1} N treatment and lowest yields were obtained in the control treatment with values of 1744 and 1320 kg ha^{-1}, respectively. These results are similar to earlier findings in canola (Gan et al., 2007) and *B. carinata* (Johnson et al., 2013; Pan.et al., 2012). Significant differences in seed yield were evident between locations, with the Brookings locations yielding significantly greater than Pierre. Lower seed yields are common in lower rainfall regions with higher maximum temperatures (Gan et al., 2004). Higher temperatures (>25 °C) during bud and flowering stages, as recorded across both locations in 2015 and 2016, can result in the abortion of flowers in *Brassica spp* and the failure of seeds to properly develop (Gan et al., 2016). Drought stress during the reproductive growth stages creates a hormone imbalance which inhibits pod formation and seed development, causing Brassica species to drop damaged flowers and focus energy into younger flowers (Canola Watch 2016). A combination of drought and heat stress can be devastating resulting in pollination failure and the formation of empty pods and subsequently, high yield losses (Gan et al, 2004). *B. carinata* is reportedly more heat and drought tolerant than *B. napus* (Taylor et al., 2010), enduring prolonged heat stress during flowering and making it a better candidate for production in the semi-arid region of South Dakota. Based on data from two years and two locations and current market prices for urea-N, the EONR for *B. carinata* production in South Dakota is ~79 kg ha^{-1} N, regardless of location (Figure 2).

Seed oil concentration decreased linearly in response to increasing N rate, similar to previous findings in *B. juncea* (May et al., 2010. In both 2015 and 2016, seed oil concentration decreased in response to N rate at both locations, but seed oil concentration was significantly higher at Brookings that at Pierre. The low oil in Pierre is most likely due to low precipitation throughout the growing season; this coupled with elevated temperatures, have been shown to be directly responsible for lower oil concentration in *Brassic*a species (Wright et al., 1998; Pritchard et al., 2000; Gan et al., 2004). Low oil concentration in semi-arid environments are likely due to accelerated growth and short growing season which negatively impact proper seed maturity and oil accumulation (Getinet et al., 1995).

While the 2015 growing season had rainfall and temperature conditions similar to the 30-year average, in 2016 Brookings and Pierre both had lower than average rainfall in June and July, coinciding with bolting, flowering, and seed fill periods, a critical time for seed development and quality. This period of drought stress during the crucial period of the growing season in 2016 contributed to the lower yield in 2016 compared to 2015. These results, in addition to the total seed yield results, show that *B. carinata* is more suited to the humid wetter cooler climates of South Dakota, but may still be productive in the semi-arid environments if conditions are conducive. Future experimentation could include use of supplemental irrigation in the semi-arid regions to compensate for periods of severe drought during the seed filling period. In addition, planting early to promote early flowering as well as the development of earlier maturing varieties with prolonged flowering periods may be beneficial; development of such varieties may reduce the yield penalty associated with drought conditions which occur during flowering and seed-filling (Kirkland and Johnson, 2000; Pritchard et al., 2000). Oil concentration must often meet certain thresholds for maximum profitability; in situations in which these standards are not met, a fee is charged for each percentage point below the standard or the seed will not be purchased at all (Pritchard et al., 2000). It is for this reason that in drier areas where irrigation is not available and oil concentrations can be sub-standard, selling seed for livestock feed or for industrial applications may be an alternative option.

Total seed oil yield increased in response to increasing N rate in a curvilinear fashion despite the decrease in seed oil concentration. These results are similar to those in previous reports (Johnson et al., 2012; May et al., 2010; Harker et al., 2012). Combined analysis showed that optimal oil yields were obtained in the 84 kg ha^{-1} N treatment before tapering off, in agreement with but slightly lower than in previous reports which showed that oil yields were optimized at ~100-125 kg ha^{-1} N (Pan et al., 2012). Total oil yields in this study increased with increasing N rate with values of 438- 542 kg ha^{-1}. These values are within the ranges reported in other studies which show oil yields ranging from 185-998 kg ha^{-1} depending on varietal and environmental conditions (Pan et al., 2012). Total seed oil yield increased in response to N rate at both locations; although on average, Brookings had significantly greater seed oil yield compared to Pierre. Higher temperatures during seed filling have a negative effect on seed oil content (Pan et al., 2012; Faraji, 2012; Canola Watch, 2016). Overall, total seed yield and oil yield increased with increasing N rate in a curvilinear manner for both locations and both varieties studied. Seed yield and oil yield increased linearly in response to increasing N rates up to 84 kg ha^{-1} N before tapering off. Primary yield gains due to increasing N rate are most likely due to increases in lateral branching, number of pods $plant^{-1}$, and bulk density of seeds rather than seeds pod^{-1}. Increases in bulk density, coupled with the increases in secondary branching and number of pods $plant^{-1}$ are the primary contributors to increased seed yields in response to increasing N rate (Seepaul et al., 2014; Anjum et al., 2012).

CONCLUSIONS

The results of the EONR analysis have determined that the optimal N rate for *B. carinata* production in South Dakota is ~84 kg ha^{-1} N regardless of environmental conditions. This suggests the potential N requirement of *B. carinata* is lower than many crops, highlighting the crop's potential as a low-input addition to current production systems in the NGP. The EONR, along with results regarding total seed yield, and total oil yield seem to reiterate the conclusions from previous research regarding optimal N rates and support the conclusions that *B. carinata* is a potential low-input crop for production in South Dakota. The contrasts between the East River (Brookings, humid-temperate. Conventional tillage) and West River and Central SD (Ideal and Pierre, semi-arid, no-till) locations have shown that *B. carinata* is more productive in the humid temperate climates of South Dakota. However, *B. carinata* may still be productive in semi-arid environments if conditions are conducive or with supplemental irrigation to compensate for periods of severe drought during the flowering and seed filling periods.

REFERENCES

Agrisoma 2015. Resonance Carinata. 2015 Production Manual- A guide to best management practices. Agrisoma. 1-18.

Angadi, S.V., H.W. Cutforth, B.G. McConkey, and Y. Gan. 2003. Crop ecology, management, and quality. Yield adjustment by canola grown at different plant populations under semi-arid conditions. Crop Sci. 43: 1358-1 366.

Anjum, N.A., S.S. Gill, S. Umar, I. Ahmad, A. Duarte, and E. Pereira. 2012. Improving growth and productivity of Oleiferous *Brassicas* under changing environments: significance of nitrogen and sulphur nutrition, and underlying mechanisms. Sci. World J. 2012: 1-12.

Brown, J., J.B. Davis, M. Lauver, and D. Wysocki. 2008. Canola growers' manual. U.S. Canola Association. 1-71.

Camberato, J., and R.L. Nelson. 2017. Nitrogen management guidelines for corn in Indiana. Purdue University Department of Agronomy. https://www.agry.purdue.edu/ext/corn/news/timeless/nitrogenmgmt.pdf. (Accessed 11 November 2017).

Canola Council of Canada. 2016. Harvest management. CCC. http://www.canolacouncil.org/canola-encyclopedia/managing-harvest/harvest-management/. (Accessed 11 November 2017).

Canola Council of Canada. 2016. Crop nutrition. CCC. https://www.canolacouncil.org/canola-encyclopedia/crop-nutrition/crop-nutrition/. (Accessed 11 November 2017).

Canola Council of Canada. 2016. Storage of canola. CCC. https://www.canolacouncil.org/canola-encyclopedia/storage-management/storage-of-canola/. (Accessed 10 11 November 2017).

Canola Watch. 2016. 7 Causes for Missing Pods. CCC. http://www.canolawatch.org/2016/06/23/7-causes-for-missing-pods/. (Accessed 11 November 2017).

Canola Watch. 2016. Top dress tips for nitrogen and sulfur. CCC. Available at http://www.canolawatch.org/2016/06/08/top-dress-tips-for-nitrogen-and-sulphur/ [Accessed 11 November 2017].

Canola Watch. 2012. How much fertilizer does canola need? CCC. http://www.canolawatch.org/2012/02/09/how-much-fertilizer-does-canola-need/ (Accessed 11 November 2017).

Cardone, M., M.V. Prati, V. Rocco, M. Seggiani, A. Senatore, and S. Vitoloi. 2002. *Brassica carinata* as an alternative oil crop for the production of biodiesel in Italy: engine performance and regulated and unregulated exhaust emissions. Environ. Sci. Technol. 36(21): 4656-4562.

deMendiburu, F. 2017. Statistical Procedures for Agricultural Research. Package ‘agricolae’ version 1.2-4.

Faraji, A. 2012. Oil Concentration in canola (*Brassica napus* L.) as a function of environmental conditions during seed filling period. Int. J. of Plant Prod. 6(3):267-278.

Franzen, D.W. 2013. Fertilizing canola and mustard. North Dakota State University Extension Service. SF1122 Revised.

Gan Y., Blackshaw, R.E., May, W.E., Vera, C., and Johnson, E.N. 2016. Yield Stability and Seed Shattering Characteristics of Brassica juncea Canola in the Northern Great Plains. Crop Sci. 56:1296-1305.

Gan, Y.K., Malhi, S.S., Brandt, S., Katepa-Mupondwa, F., and Kutcher, H.R. 2007. *Brassica juncea* canola in the Northern Great Plains: responses to diverse environments and nitrogen fertilization. Agron. J. 99:1208-1218.

Gan, T., S.V. Angadi, H. Cutforth, D. Potts, V.V. Angadi, and C.L. McDonald. 2004. Canola and mustard response to short periods of temperature and water stress at different developmental stages. Can. J. Plant Sci. 84: 697-704.

Getinet, A., G. Rakow, R.K. and Downey. 1995. Agronomic performance and seed quality of Ethiopian Mustard in Saskatchewan. Can. J. Plant Sci. 76:387-392.

Godsey, C., R. Taylor, and M. Boyles. 2013. No-till winter canola considerations. Oklahoma Cooperative Extension Service. PSS-2153.

Grant, C.A. and L.D. Bailey. 1993. Fertility management in canola production. Canadian Journal of Plant Science 73:651-670.

Harker, K.N., J.T. O'Donovan, T.K. Turkington, R.E. Blackshaw, N.Z. Lupwayi, E.G. Smith, H. Klein-Gebbinck, L.M. Dosdall, L.M. Hall, C.J. Willenborg, H.R. Kutcher, S.S. Malhi, C.L. Vera, Y. Gan, G.P. Lafond, W.E. May, C.A. Grant, and D.L. McLaren. 2012. High-yield no-till canola production on the Canadian prairies. Can. J. Plant Sci. 92:221-233.

Hanson, B.K., B.L. Johnson, R.A. Henson, and N.R. Riveland. 2008. Seeding rate, seeding depth, and cultivar influence on spring canola performance in the Northern Great Plains. Agron. J. 100: 1339-1 345.

Hocking, P.J., J.A. Kirkegaarda, J.F. Angusa, A. Bernardib, and L.M. Masona. 2002. Comparison of canola, Indian mustard, and Linola in two contrasting environments: III. Effects of nitrogen fertilizer on nitrogen uptake by plants and on soil nitrogen extraction. Field Crops Res. 79:153-172.

Jackson, G.D. 2000. Effects of nitrogen and sulfur on canola yield and nutrient uptake. Agron. J. 92:644-649.

Jones, C. and K. Olson-Rutz. 2016. Soil nutrient management for canola. Montana State University Extension. EB0224.

Johnson, E.N., S.S. Malhi, L.M. Hall, and S. Phelps. 2013. Effects of nitrogen fertilizer application on seed yield, N uptake, N use efficiency, and seed quality of *Brassica carinata*. Can. J. Plant Sci. 93: 1073-1081.

Karamzadeh, A., H.R. Mobasser, V. Ramee, and A. Ghanbari-Malidarreh. 2010. Effects of nitrogen and seed rates on yield and oil content of canola (*Brassica napus*). American-Eurasian J. Agric. & Environ. Sci. 8 (6): 715-721.

Kirkland, K.J. and E.N. Johnson. 2000. Alternative seeding date (fall and April) affect *Brassica napus* canola yield and quality. Can. J. Plant Sci. 80: 713-719.

Koening, R.T., A. Hammac, and W.L. Pan. 2011. Canola growth, development, and fertility. Washington State University Extension. FS045E.

Kutcher, K.M., H.R. Kirkland, and E. Johnson. 2000. Effect of early spring seeding on diseases of canola. University of Saskatchewan Soils & Crops. http://www.usask.ca/soilsncrops/conference-proceedings/previous_years/Files/2000/2000docs/167.pdf. (Accessed 17 November 2017).

Marquard, R. and A. Gendy. 1989. Studies on the effect of nitrogen fertilization and growth regulators on seed-yield and some quality criteria of oilseed-rape (*Brassica napus* L.). Fett Wissenschaft Technology. 9: 353-357.

May, W.E., S.A. Brandt, Y. Gan, H.R. Kutcher, C.B. Holzapfel, and G.P. Lafond. 2010. Adaptation of oilseed crops across Saskatchewan. Can. J. Plant Sci. 90: 667-677.

Mckenzie, R.H., E. Bremer, A.B. Middleton, P.G. Pfiffner, and S.A. Woods. 2011. Effect of seeding date and rate for irrigated grain and oilseed crops in southern Alberta. Can. J. Plant Sci. 91:293-303.

Morrison, M.J. and D.W. Stewart. 2002. Heat stress during flowering in summer rape. Crop Sci. 42:797-803

Pan, X., C.D. Caldwell, K.C. Falk, and R. Lada. 2012. The effect of cultivar, seeding rate, and applied nitrogen on *Brassica carinata* seed yield and quality in contrasting environments. Can. J. Plant Sci. 92: 961-971.

Potts, D.A., G.W. Rakow, D.R. Males, and D.L. Woods. 2003. The development of canola-quality *Brassica juncea*. Can J. Plant Sci. 83:117-118.

Pritchard, F.M., H.A. Eagles, R.M. Norton, P.A. Salisbury, and M. Nicolas. 2000. Environmental effects on seed composition of Victorian canola. Aust. J. of Exp. Agric. 40: 679-685.

Seepaul, R., D.L. Wright, C.M. Bliss, S. George, and J.J. Marois. 2014. The effects of planting date and N application rate on *Brassica carinata* production in north Florida. North Florida Research and Education Center. ASA-CSSA-SSSA 2014 Annual Meeting.

https://dl.sciencesocieties.org/publications/meetings/download/pdf/2014am/87656. (Accessed 17 November 2017).

Sitter, T. 2017. Personal communication. Northern Plains Commodities, LLC. August 8 2017.

Taylor, D.C., K.C. Falk, C.D. Palmer, J. Hammerlindl, V. Babic, E. Mietkiewska, A. Jadhav, E.F. Marillia, T. Francis, T. Hoffman, E.M. Giblin, V. Katavic, and W.F. Keller. 2010. *Brassica carinata*- a new molecular farming platform for delivering bio-industrial oil feedstocks: case studies of genetic modifications to improve very long-chain fatty acid and oil content in seeds. Biofuels Bioprod. Bioref. 4:538-561.

Taylor, A. J., C.J. Smith, and I.B. Wilson. 1991. Effect of irrigation and nitrogen fertilizer on yield, oil content, nitrogen accumulation and water use of canola (*Brassica napus* L.). Fert. Res. 29: 249-250.

Wright, G. C., C.J. Smith, and M.R. Woodroffe. l998. The effect of irrigation and nitrogen fertilizer on rapeseed (*Brassica napus*) production in south-eastern Australia. Irrig. Sci. 9: l-13.

Zentner, R.P., D.D. Wall, C.N. Nagy, E.G. Smith, D.L. Young, P.R. Miller, C.A. Campbell, B.G. McConkey, S.A. Brant, G.P. Lafond, A.M. Johnston, and D.A. Derksen. 2002. Economics of crop diversification and soil tillage opportunities in the Canadian prairies. Agron. J. 94:216-230.

Zanetti, F., T. Vamerali, and G. Mosca. 2009. Yield and oil variability in modern varieties of high-Euric winter oilseed rape (*Brassica napus* L. var. *olefifera*) and

Ethiopian Mustard (*Brassica carinata* A. Braun) under reduced agricultural inputs. Ind. Crops Prod. 30:265-270.

Table 2.1. Soil physical and chemical characteristics for both years and locations.

Location	Year	Previous Crop	Depth (in)	Texture Class	pH	Soluble Salts (mmho/cm)	Organic Matter (%)	Nitrogen-NO3 (ppm)	Olsen-P (ppm)	K (ppm)
Brookings	2015	WW	0-6	Medium	5.7	0.2	4.8	12.0	9.0	171.0
Brookings	2016	WW	0-6	Medium	5.6	0.1	4.8	12.0	16.0	349.0
Pierre	2015	Corn	0-6	Medium	6.1	0.2	2.9	10.8	8.9	208.0
Pierre	2016	Corn	0-6	Medium	6.1	0.2	3.0	18.1	21.7	626.0

WW = Winter Wheat

Table 2.2. Monthly temperature data collected throughout the growing period (GP) for all environments (2015 and 2016) in South Dakota (numbers in parentheses indicate differences from 1981-2010 average).

	April		***May***		***June***		***July***		***August***	
Temp. (ºC)	Max	Avg.	Max	Avg.	Max	Avg.	Max	Avg.	Max	Avg.
Brookings 2015	**15.8 (+3.0)**	**8.7 (+2.0)**	**18.6 (-0.8)**	**13.0 (-0.3)**	**25.1 (+0.1)**	**19.6 (+0.7)**	**27.3 (-0.5)**	**21.7 (+0.6)**	**25.1 (-1.6)**	**19.5 (-0.5)**
Brookings 2016	**13.8 (+1.0)**	**7.9 (+1.2)**	**20.8 (+1.4)**	**14.6 (+1.3)**	**27.3 (+2.3)**	**21.3 (+2.4)**	**27.1 (-0.7)**	**21.6 (+0.5)**	**26.3 (-0.4)**	**20.9 (+0.9)**
Pierre 2015	**17.7 (+2.1)**	**9.8 (+1.5)**	**19.3 (-1.8)**	**12.9 (-1.5)**	**27.1 (+0.4)**	**20.6 (+0.6)**	**30.9 (-0.8)**	**23.4 (-0.5)**	**30.0 (-0.6)**	**22.6 (-0.7)**
Pierre 2016	**15.8 (+0.2)**	**8.9 (+0.6)**	**22 (+0.9)**	**14.4 (0)**	**30.1 (+4.4)**	**22.2 (+2.2)**	**32.3 (+0.6)**	**24.4 (+0.5)**	**30.2 (+0.4)**	**22.7 (+0.6)**

Table 2.3. Monthly rainfall data collected throughout the growing period (GP) for all environments (2015 and 2016) in South Dakota (numbers in parentheses indicate differences from 1981-2010 average).

	April	***May***	***June***	***July***	***August***	***Total GP Rainfall***
Rainfall (mm)						
Brookings 2015	**5.1 (-49.0)**	**137.2 (+62.3)**	**43.2 (-65.8)**	**111.8 (+28.7)**	**71.1 (-6.9)**	**368.3 (-30.7)**
Brookings 2016	**48.3 (-5.8)**	**60.2 (-14.7)**	**66 (-43.0)**	**124.5 (+41.4)**	**142.2 (+64.2)**	**441.2 (+42.2)**
Pierre 2015	**12.4 (-33.6)**	**157.0 (+77.0)**	**96.2 (+6.4)**	**58.2 (-7.4)**	**63.2 (+17.2)**	**387 (+58.6)**
Pierre 2016	**99.6 (+53.6)**	**30.5 (-49.5)**	**70.8 (-19.6)**	**65.6 (-37.2)**	**54.4 (+8.4)**	**320.9 (-7.5)**

Table 2.4. Total days with temperatures above 25 and 30 °C and precipitation for N fertility experiments during critical growth stages conducted at Brookings, SD in 2015 and 2016.

	Month	Days	Days > 25 ºC	Days > 30 ºC	Precipitation (mm)
2015	June	1-10	6	1	10.2
	June	11-20	4	0	5.1
	June	21-30	7	0	27.9
	July	1-10	5	1	48.3
	July	11-20	10	3	0.0
	July	21-31	11	1	63.5
					Total = 154.9
2016	June	1-10	4	2	15.2
	June	11-20	10	4	48.3
	June	21-30	8	0	2.5
	July	1-10	5	1	81.3
	July	11-20	8	2	20.3
	July	21-31	10	3	22.9
					Total = 190.5

Table 2.5. Total days with temperatures above 25 and 30 °C and precipitation for N fertility experiments during critical growth stages conducted at Pierre, SD in 2015 and 2016.

	Month	Days	Days > 25 ºC	Days > 30 ºC	Precipitation (mm)
2015	June	1-10	6	3	2.8
	June	11-20	7	1	62.9
	June	21-30	9	3	30.5
	July	1-10	8	3	35.8
	July	11-20	10	7	7.6
	July	21-31	11	10	14.7
					Total = 154.3
2016	June	1-10	8	3	16.0
	June	11-20	9	5	31.0
	June	21-30	10	5	23.9
	July	1-10	9	6	22.9
	July	11-20	10	8	5.3
	July	21-31	11	8	0.3
					Total = 99.3

Table 2.6. P-values from ANOVA for plant height, lodging, days to maturity, pod shatter, seed yield, oil concentration and oil yield of *B. carinata*. Data are combined over two locations in South Dakota (Brookings and Pierre), two years (2015 and 2016) and two varieties.

Source	df	Height	Days to Maturity	Lodging Severity	Shatter	Seed Yield	Oil Concentration	Oil Yield
N Rate (NR)	**4**	**≤ .001**	**≤ .001**	**0.134**	**0.708**	**≤ .001**	**≤. 001**	**≤. 001**
Location (L)	**1**	**≤ .001**	**0.001**	**< .001**	**0.001**	**≤ .001**	**≤. 001**	**≤. 001**
Variety (V)	**1**	**0.230**	**0.697**	**0.096**	**0.017**	**0.046**	**0.369**	**0.094**
NR x L	**4**	**0.884**	**0.111**	**0.555**	**0.116**	**0.576**	**0.271**	**0.343**
NR x V	**4**	**0.475**	**0.082**	**0.837**	**0.628**	**0.349**	**0.25**	**0.301**
L x V	**1**	**0.002**	**0.766**	**0.558**	**0.06**	**0.668**	**0.58**	**0.744**
NR x L x V	**4**	**0.17**	**0.442**	**0.468**	**0.141**	**0.091**	**0.14**	**0.248**
Components of variance for random effects		**Estimate**	**Estimate**	**Estimate**	**Estimate**	**Estimate**	**Estimate**	**Estimate**
σ Location:Year:Replication		**8.0**	**28.8**	**4.7**	**28.8**	**11566.3**	**3.8**	**6148.2**
σ Residual		**40.6**	**14.4**	**1.0**	**15.4**	**72072.1**	**1.76**	**7414.9**

Table 2.7. N rate effects on plant height, lodging severity, days to maturity, pod shatter, seed yield, oil concentration and oil yield in *B. carinata* grown in SD. Means are averages over two locations (Brookings and Pierre), two years (2015 and 2016), and two varieties.

N Rate (kg ha^{-1})	Height (cm)	Lodging Severity (1-9)	Days to Maturity	Shatter (%)	Seed Yield (kg ha^{-1})	Oil Con. (g kg-^{1})	Oil Yield (kg ha^{-1})
0	**98 (c)***	**2.4 (b)**	**111 (bc)**	**3.9**	**1320 (c)**	**338 (a)**	**439 (b)**
28	**104 (b)**	**2.8 (ab)**	**112 (b)**	**3.6**	**1546 (b)**	**330 (b)**	**507 (a)**
56	**107 (ab)**	**2.4 (b)**	**113 (ab)**	**2.9**	**1615 (ab)**	**323 (c)**	**520 (a)**
84	**108 (a)**	**2.6 (ab)**	**114 (a)**	**3.2**	**1744 (a)**	**312 (d)**	**542 (a)**
140	**110 (a)**	**3.0 (a)**	**114 (a)**	**2.6**	**1717 (a)**	**299 (e)**	**514 (a)**
Mean	**106**	**2.6**	**113**	**3.2**	**1588**	**320**	**504**

*Within each column, means followed by the same letter are not significantly different (P≤0.05).

Table 2.8. Location and variety effects on plant height, lodging severity, days to maturity, pod shatter, seed yield, oil concentration and oil yield in *B. carinata* grown in South Dakota. Means are averages over five N rates and two years (2015 and 2016).

Location/ Variety	Height (cm)	Lodging Severity	Days to Maturity	Shatter (%)	Seed Yield (kg ha^{-1})	Oil Con. (g kg^{-1})	Oil Yield (kg ha^{-1})
Location							
Brookings	**102 (b)***	**1.8 (b)**	**112**	**1.3 (b)**	**1690(a)**	**347 (a)**	**582(a)**
Pierre	**109 (a)**	**3.4 (a)**	**113**	**5.1 (a)**	**1486 (b)**	**294 (b)**	**427 (b)**
Mean	**105.5**	**20.6**	**113**	**3.2**	**1588**	**320**	**504**
Variety							
A110	**104.1**	**2.6**	**113**	**4.0 (a)**	**1546**	**321**	**515**
A120	**106.1**	**2.7**	**112**	**2.4 (b)**	**1630**	**319**	**493**
Mean	**105.1**	**2.7**	**113**	**3.1**	**1588**	**32**	**504**

*Within each column, means followed by the same letter are not significantly different (P≤0.05).

Table 2.9. P-values from ANOVA for seeds per pod and bulk density of *B. carinata* at two locations in SD (Brookings and Pierre) in 2016.

Source	df	Seeds pod^{-1}	Bulk density (g .47L^{-1})
N Rate (NR)	**4**	**≤.001**	**≤.001**
Location (L)	**1**	**0.574**	**0.371**
Variety (V)	**1**	**0.036**	**≤.001**
NR x L	**4**	**0.002**	**0.613**
NR x V	**4**	**0.068**	**0.19**
L x V	**1**	**0.701**	**0.183**
Components of variance for random effects		**Estimate**	**Estimate**
σ Location:Replication		**≤.001**	**37.70**
σ Residual		**1.58**	**224.0**

Table 2.10. N rate effects on seeds per pod and bulk density of *B. carinata* grown at Brookings and Pierre, in 2016. Means are averages over two varieties; seeds pod^{-1} was evaluated separately due to a significant Location x N Rate interaction.

N Rate (kg ha^{-1})	Seeds pod^{-1}		Bulk density (g .47L^{-1})
	Pierre	***Brookings***	
0	**14 (bc)***	**16.0**	**338.1 (c)**
28	**17 (a)**	**15**	**342 (bc)**
56	**16 (a)**	**16**	**353 (a)**
84	**15 (ab)**	**16**	**352 (ab)**
140	**15 (ab)**	**16**	**353 (ab)**
Mean	**16**	**16**	**348**

*Within each column, means followed by the same letter are not significantly different (P≤0.05).

Table 2.11. Location and variety effects on seeds per pod, and bulk density in *B. carinata* grown at Brookings and Pierre, in 2016. Means are averages over two varieties.

Location/Variety	Seeds pod^{-1}	Bulk density (g .47L^{-1})
Location		
Brookings	**16**	**346**
Pierre	**16**	**349**
Mean	**16**	**348**
Variety		
A110	**15 (b)***	**340 (b)**
A120	**16 (a)**	**355 (a)**
Mean	**16**	**348**

*Within each column, means followed by the same letter are not significantly different (P≤0.05).

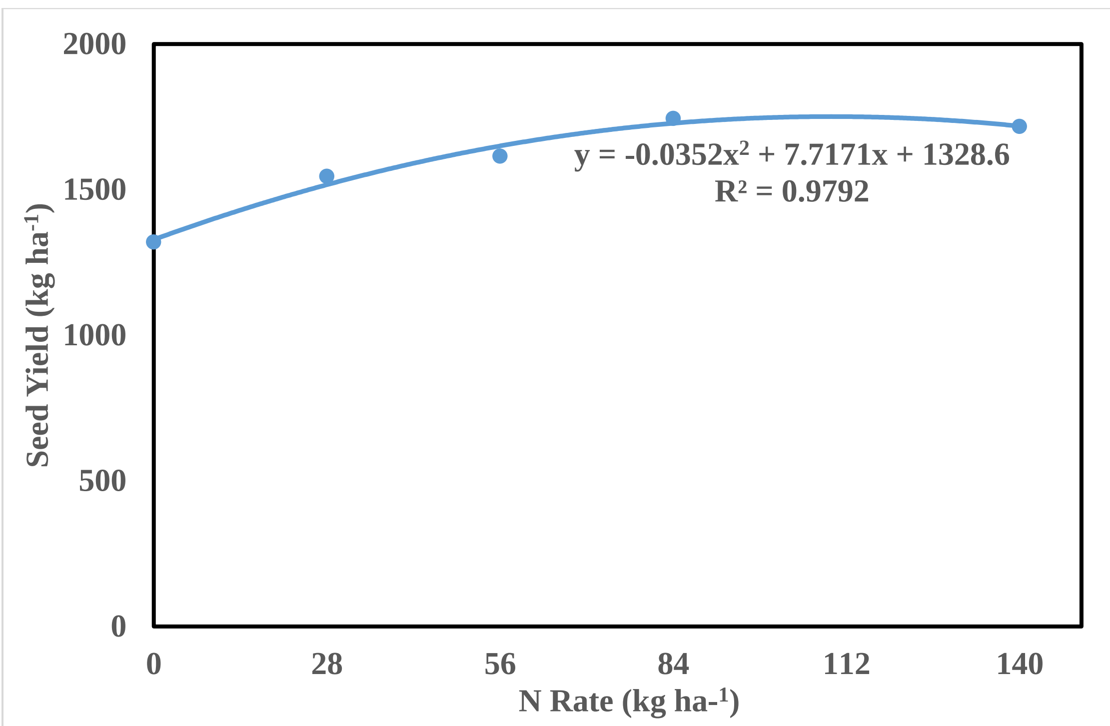

Figure 2.1. Seed yield response to N fertilizer rate for *B. carinata* grown at two locations, Brookings and Pierre. Means are averaged over two years (2015 and 2016) and two varieties. Polynomial equation used to determine EONR.

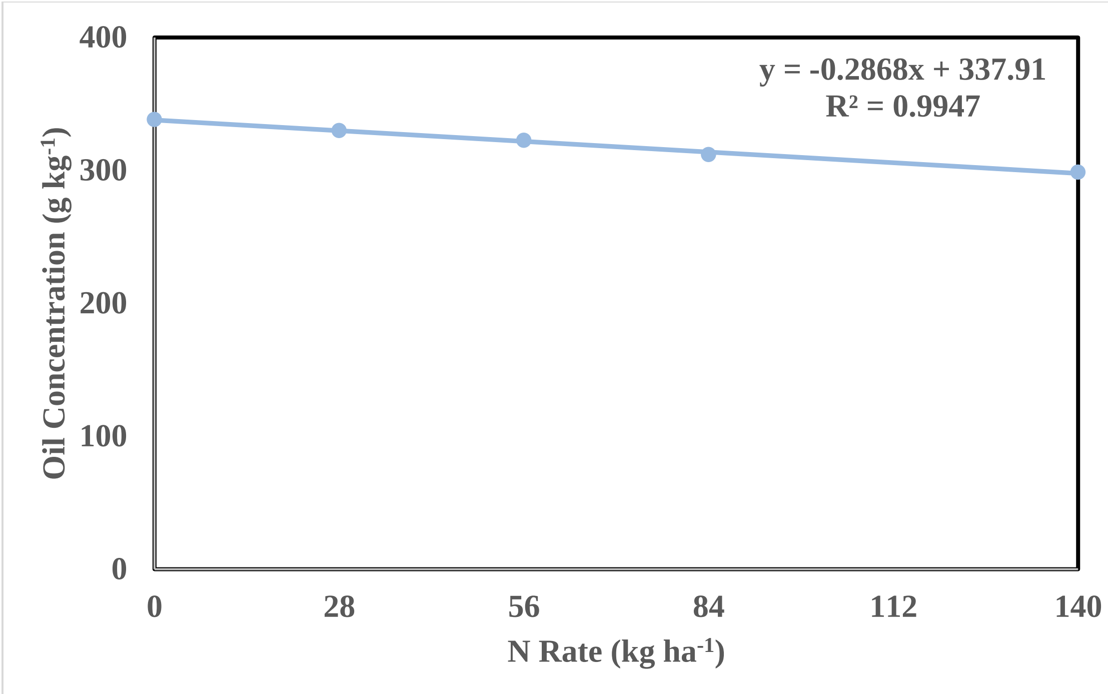

Figure 2.2. Seed oil concentration response to N fertilizer rate for *B. carinata* grown at two locations, Brookings and Pierre. Means are averaged over two years (2015 and 2016) and two varieties.

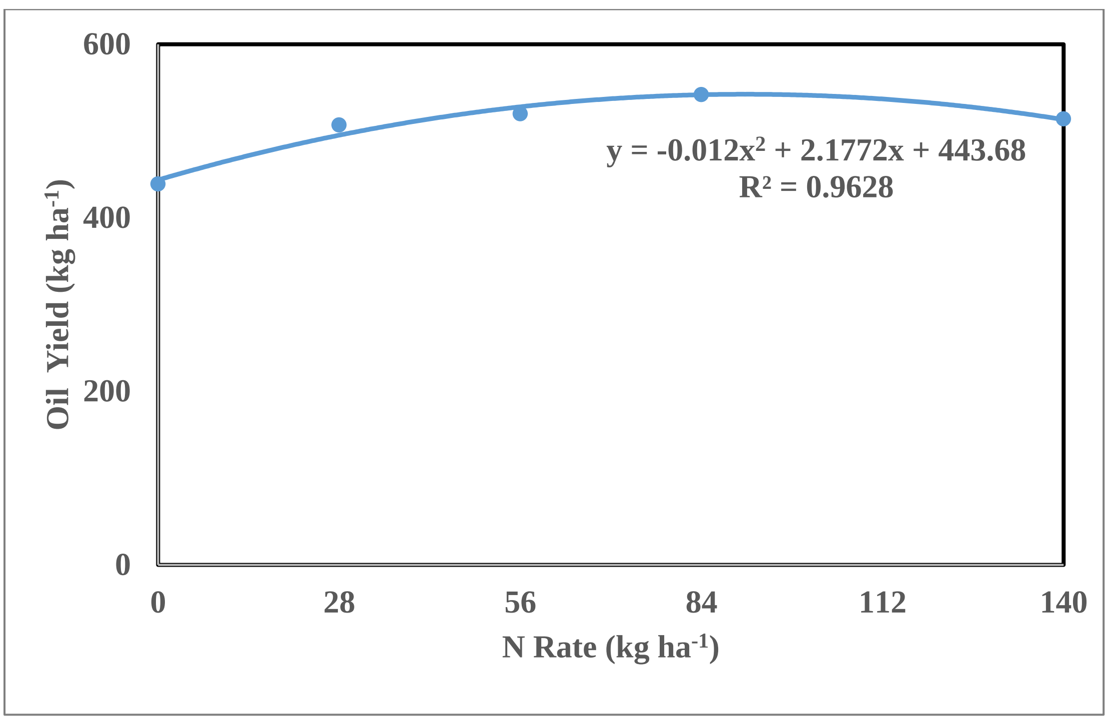

Figure 2.3. Oil yield (kg ha^{-1}) response to N fertilizer rate for *B. carinata* grown at Brookings and Pierre. Means are averaged over two years (2015 and 2016) and two varieties.

CONCLUSIONS AND RECOMMENDATIONS

South Dakota has extremely diverse climates ranging from humid temperate (Eastern SD) to semi-arid (West River and Central SD). Variation in climatic conditions and crop production systems among these regions can have significant impacts on optimal seeding rates and fertilizer inputs. Our study determined the optimum seeding rate and N rate for *B. carinata* production at two environments in South Dakota. The results of this research show that optimal seeding rates for the East River (Brookings) and West River and Central SD (Ideal and Pierre) are ~10 and ~13 kg $ha^{-1,}$ respectively. In Brookings the crop was grown under conventional till while at Ideal and Pierre, the crop was grown under no-till. The results suggest that higher seeding rates may be necessary to help compensate for reduced stand establishment under no-till and subsequent yield reductions due to drought in Central and West River SD. On the other hand, the optimal N rate for *B. carinata* production in South Dakota was determined to be ~79 kg ha^{-1} N regardless of location. These results confirm that *B. carinata* is a low input crop compared to corn or small grains and illustrate the potential for incorporating the crop into current production systems as a low-input option.

In conclusion, *B. carinata* appears to have higher yield potential East River due to a more favorable environment for growth and yield. *B.carinata* but may still be a productive in Central and Western SD if environmental conditions are conducive as was the case in 2015 and 2016. In drier years like 2017 for example, the crop is low yielding and may require supplemental irrigation during the flowering and seed-filling periods to preserve yield potential. In addition, development of new varieties to improve yield potential, as well as the development of varieties with early flowering, prolonged flowering periods, and earlier maturing dates may be beneficial to pursue. Lastly, seed oil concentration is often the greatest metric of profitability for producers. However, because environmental conditions (temperature and rainfall) can have significant impacts on seed oil yield, it is important to consider production goals when considering crop inputs (seeding rates and N rates). In environments where it is not feasible for oil concentrations to meet the required thresholds for maximum profitability, selling seed for meal or for industrial applications may be an option.

APPENDIX

Table A.1. P values from ANOVA for plant stand, plant height, lodging severity, pod shatter, days to maturity, number of pods per plant, number of seeds per pod, seed yield, oil concentration and oil yield of *B. carinata.* Data combined over five environments: Brookings (2016 and 2017), Pierre, and Ideal in 2016 and 2017.

Source	**df**	**Plant Stand**	**Plant Height**	**Lodging**	**Shatter**	**Pods Plant $^{-1}$**	**Seeds Pod $^{-1}$**	**Seed Yield**	**Oil Con.**	**Oil Yield**
Seeding Rate (SR)	**3**	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	0.217	≤ .001	0.972	0.019
Environment (E)	**4**	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001	≤ .001
Variety (V)	**2**	0.218	0.004	0.851	0.038	0.003	≤ .001	≤ .001	≤ .001	0.005
SR x E	**12**	≤ .001	0.002	≤ .001	≤ .001	0.671	0.449	≤ .001	≤ .001	0.002
SR x V	**6**	0.325	0.054	0.138	0.185	0.93	0.542	0.385	0.564	0.317
E x V	**3**	0.203	≤ .001	0.885	0.193	0.083	0.182	≤ .001	≤ .001	0.169
SR x E x V	**9**	0.946	0.148	0.221	0.986	0.916	0.259	0.341	0.232	0.244
Components of variance for random effects		**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**
σ E:Rep		27.7	1.9	4.8	0.15	373.5	0.191	969.58	0.649	404.9
σ Residual		207.2	11.7	4.8	10.2	1822.2	2.76	13865.9	4.10	2324.1

Table A.2. P values from ANOVA for plant stand, plant height, lodging severity, pod shatter, days to maturity, number of pods per plant, number of seeds per pod, seed yield, oil concentration and oil yield of *B. carinata* at Brookings in 2016.

Source	df	Plant Stand	Plant Height	Lodging	Shatter	Pods Plant $^{-1}$	Seeds Pod $^{-1}$	Flower Days	Maturity Days	Seed Yield	Oil Con.	Oil Yield
Seeding Rate (SR)	**3**	**≤ .001**	**≤ .001**	**≤ .001**	**≤ .001**	**0.004**	**0.011**	**0.846**	**≤ .001**	**0.013**	**0.217**	**0.036**
Variety (V)	**1**	**0.848**	**0.650**	**0.577**	**0.374**	**0.747**	**0.783**	**0.002**	**≤ .001**	**0.003**	**0.081**	**0.067**
Replication (R)	**3**	**0.096**	**0.845**	**0.462**	**0.963**	**0.514**	**0.009**	**0.846**	**0.619**	**0.429**	**0.188**	**0.395**
SR x V	**3**	**0.749**	**0.645**	**0.059**	**0.799**	**0.19**	**0.0177**	**0.846**	**0.023**	**0.456**	**0.181**	**0.371**
Components of variance for random effects		**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**
σ Replication		**42.2**	**≤ .001**	**1.19**	**≤ .001**	**0.008**	**0.3855**	**3.86**	**≤ .001**	**0.2**	**0.47**	**35.4**
σ Residual		**240.2**	**7.2**	**8.76**	**8.51**	**299.74**	**0.7877**	**4.24**	**0.602**	**36637.1**	**5.1**	**6856.5**

Table A.3. P values from ANOVA for plant stand, plant height, lodging severity, pod shatter, days to maturity, number of pods per plant, number of seeds per pod, seed yield, oil concentration and oil yield of *B. carinata* at Brookings in 2017.

Source	df	Plant Stand	Plant Height	Lodging	Shatter	Pods Plant $^{-1}$	Seeds Pod $^{-1}$	Flower Days	Maturity Days	Seed Yield	Oil Con.	Oil Yield
Seeding Rate (SR)	**3**	**≤ .001**	**≤ .001**	**≤ .001**	**0.062**	**0.613**	**0.449**	**≤.001**	**≤ .001**	**0.074**	**0.172**	**0.507**
Variety (V)	**1**	**0.014**	**0.478**	**1.00**	**0.725**	**0.175**	**0.033**	**0.898**	**0.05**	**0.071**	**≤ .001**	**0.082**
Replication (R)	**3**	**0.978**	**0.303**	**0.806**	**0.505**	**0.001**	**0.2749**	**0.652**	**0.815**	**0.016**	**0.023**	**0.001**
SR x V	**3**	**0.481**	**0.951**	**0.342**	**0.709**	**0.769**	**0.7422**	**0.474**	**0.324**	**0.078**	**0.726**	**0.128**
Components of variance for random effects		**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**
σ Replication		**0.02**	**0.188**	**5.4**	**≤ .001**	**494.4**	**0.116**	**≤.001**	**≤ .001**	**4483.6**	**2.0**	**2003.80**
σ Residual		**175.1**	**5.18**	**6.4**	**6.14**	**601.2**	**2.417**	**1.86**	**1.5**	**10714.2**	**5.6**	**2470.9**

Table A.4. P values from ANOVA for plant stand, plant height, lodging severity, pod shatter, days to maturity, number of pods per plant, number of seeds per pod, seed yield, oil concentration and oil yield of *B. carinata* at Pierre in 2016.

Source	df	Plant Stand	Plant Height	Lodging	Shatter	Pods Plant $^{-1}$	Seeds Pod $^{-1}$	Seed Yield	Oil Con.	Oil Yield
Seeding Rate (SR)	3	0.006	≤ .001	≤ .001	≤ .001	≤ .001	0.301	0.002	0.125	0.002
Variety (V)	1	0.332	0.988	0.607	0.007	0.651	0.162	0.055	0.954	0.057
Replication (R)	3	0.187	0.273	0.0914	0.199	0.725	0.364	0.173	0.004	0.476
SR x V	3	0.408	0.072	0.844	0.107	0.404	0.569	0.162	0.636	0.122
Components of variance for random effects		Est.	Est.	Est.	Est.	Est.	Est.	Est.	Est.	Est.
σ Replication		29.8	0.264	0.0221	0.744	0.009	0.0148	766.8	0.37	0.014
σ Residual		316.7	5.41	0.114	8.63	131.031	0.9986	7393.4	0.62	800.3

Table A.5. P values from ANOVA for plant stand, plant height, lodging severity, pod shatter, days to maturity, number of pods per plant, number of seeds per pod, seed yield, oil concentration and oil yield of *B. carinata* at Pierre in 2017.

Source	df	Plant Stand	Plant Height	Lodging	Shatter	Pods Plant $^{-1}$	Seeds Pod $^{-1}$	Seed Yield	Oil Con.	Oil Yield
Seeding Rate (SR)	**3**	**0.004**	**0.002**	**0.044**	**≤ .001**	**0.526**	**0.668**	**0.199**	**0.136**	**0.180**
Variety (V)	**1**	**0.832**	**0.440**	**0.652**	**0.279**	**0.057**	**0.596**	**0.026**	**0.681**	**0.026**
Replication (R)	**3**	**0.047**	**0.167**	**0.8392**	**0.219**	**0.087**	**0.315**	**0.743**	**0.541**	**0.673**
SR x V	**3**	**0.915**	**0.356**	**0.7895**	**0.746**	**0.854**	**0.714**	**0.091**	**0.328**	**0.125**
Components of variance for random effects		**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**
σ Replication		**65.4**	**1.44**	**5.36**	**1.71**	**1436.98**	**0.214**	**0.1**	**≤ .001**	**0.002**
σ Residual		**244.5**	**13.37**	**5.95**	**22.7**	**7656.4**	**6.728**	**507.6**	**6.6**	**34.8**

Table A.6. P values from ANOVA for plant stand, plant height, lodging severity, pod shatter, days to maturity, and number of pods per plant, number of seeds per pod, seed yield, oil concentration and oil yield of *B. carinata* at: Ideal in 2017.

Source	df	Plant Stand	Plant Height	Lodging	Shatter	Pods Plant $^{-1}$	Seeds Pod $^{-1}$	Seed Yield	Oil Con.	Oil Yield
Seeding Rate (SR)	**3**	**≤ .001**	**0.018**	**≤ .001**	**0.077**	**≤ .001**	**0.2317**	**0.102**	**≤ .001**	**0.069**
Variety (V)	**1**	**0.685**	**0.001**	**0.686**	**0.427**	**0.043**	**0.001**	**0.922**	**0.852**	**9352**
Replication (R)	**3**	**0.024**	**0.036**	**0.018**	**1.000**	**0.951**	**0.215**	**0.462**	**0.616**	**0.409**
SR x V	**3**	**0.172**	**0.077**	**0.917**	**0.588**	**0.247**	**0.091**	**0.985**	**0.351**	**0.997**
Components of variance for random effects		**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**	**Est.**
σ Replication		**2.4**	**8.3**	**0.0744**	**≤ .001**	**0.047**	**0.222**	**0.2**	**0.61**	**1.49**
σ Residual		**59.6**	**27.2**	**0.186**	**4.7**	**422.7**	**2.887**	**14077.2**	**2.6**	**1458.1**

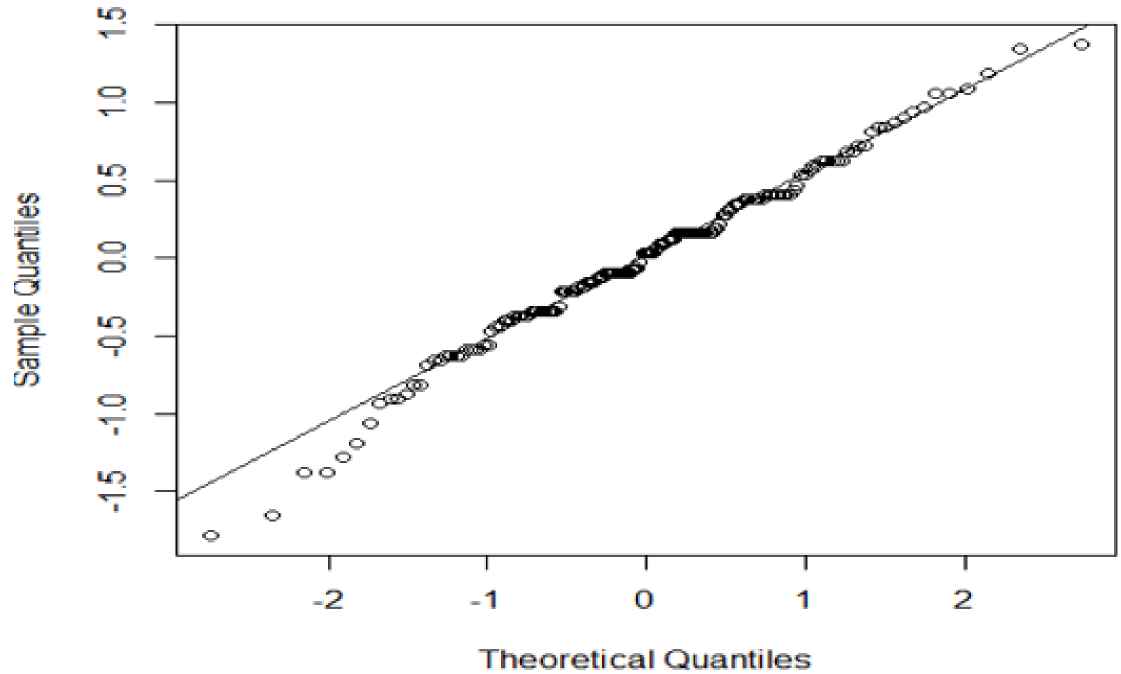

Figure A.1. Q-Q plot for lodging scores collected during *B. carinata* seeding rate studies conducted at five environments in 2016 and 2017.

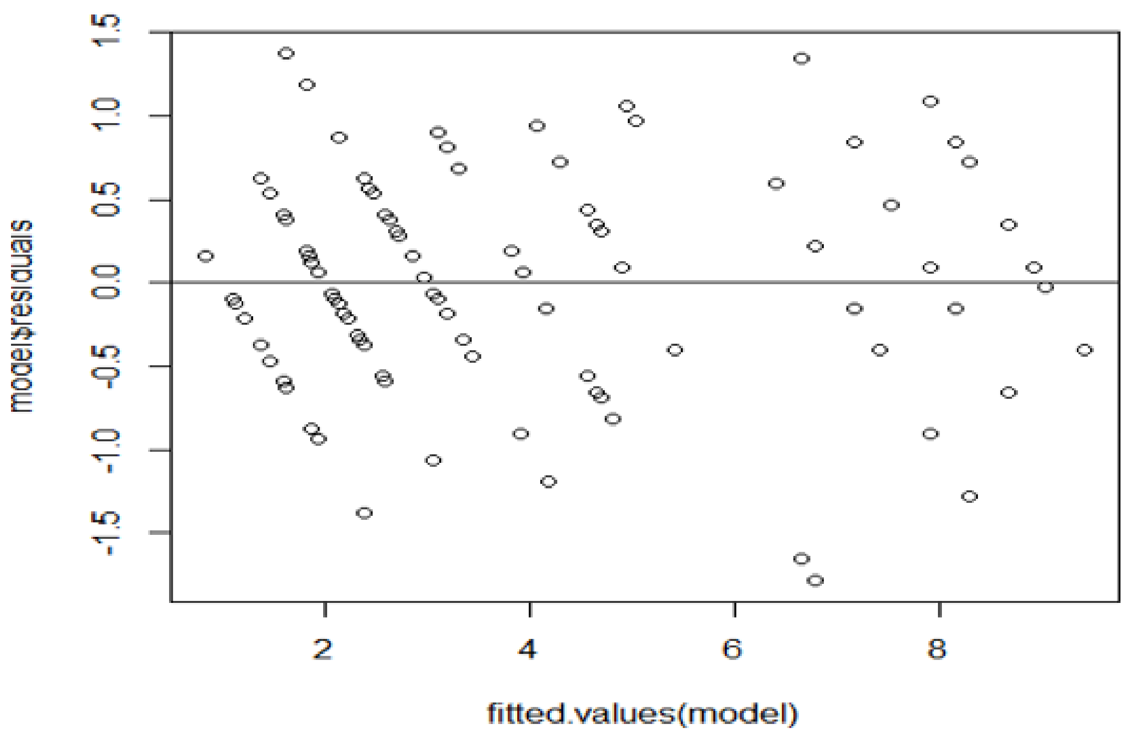

Figure A.2. Residuals versus fitted values plot for lodging scores collected during *B. carinata* seeding rate studies conducted at five environments in 2016 and 2017.